Large Eddy Simulation of Airfoil Self-Noise

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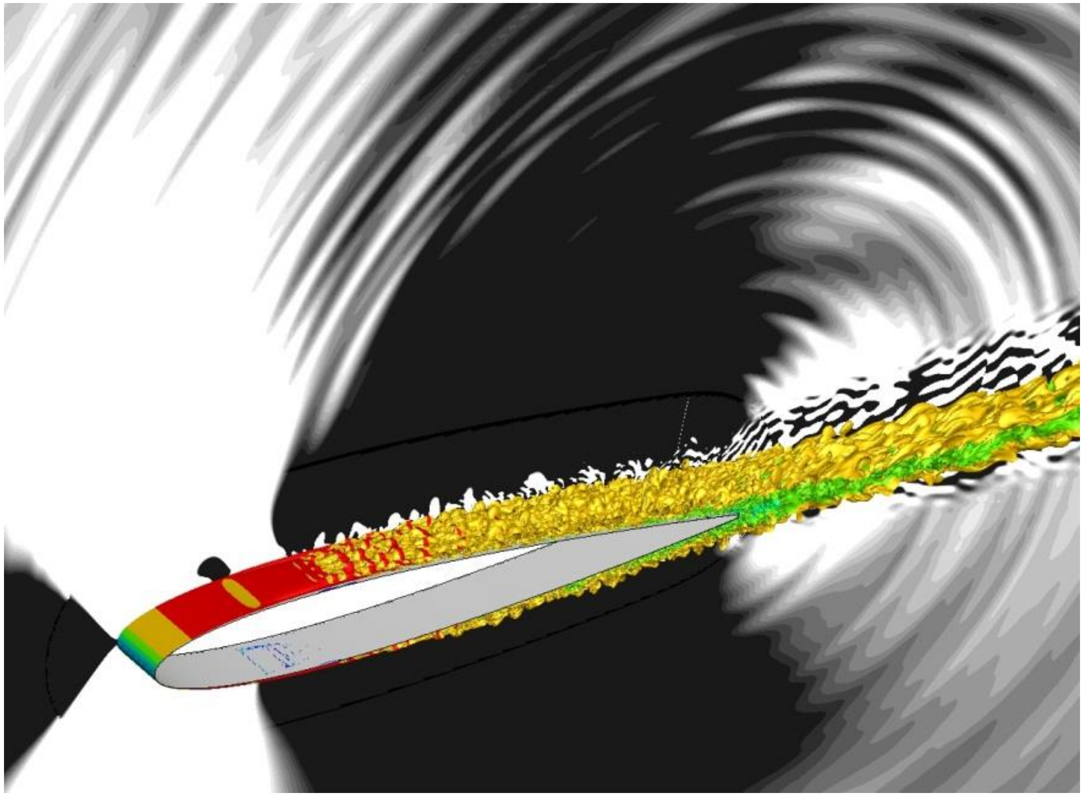
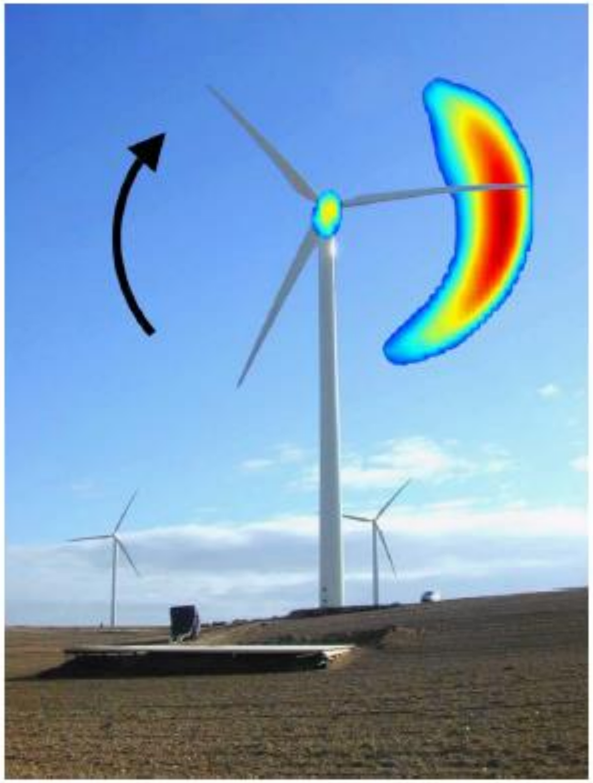
Introduction



- Noise generated by a turbulent boundary layer that encounters the trailing edge of an airfoil

Fig: Wolf *et al.*, 2012

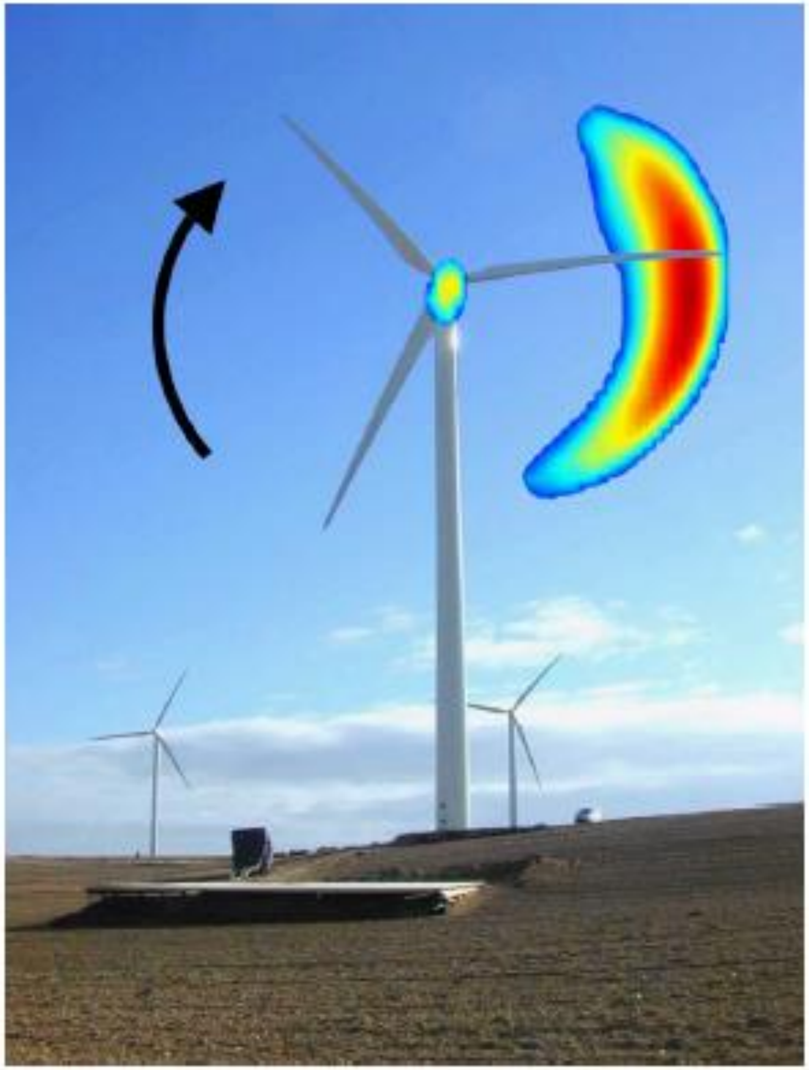
Motivation



Google Images

Oerlemans *et al.*, 2007

The need for HPC



- Trailing edge noise dominates modern wind turbine noise
- Are semi-empirical wind turbine noise prediction methods robust enough?
- RANS not reliable for predicting aerodynamic stall
- Aerodynamics and acoustics from first principles – a pacing item and a challenge

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J. G. Kocheemoolayil, M.Barone, S. K. Lele, G. Jothiprasad and L. Cheung, *under preparation*

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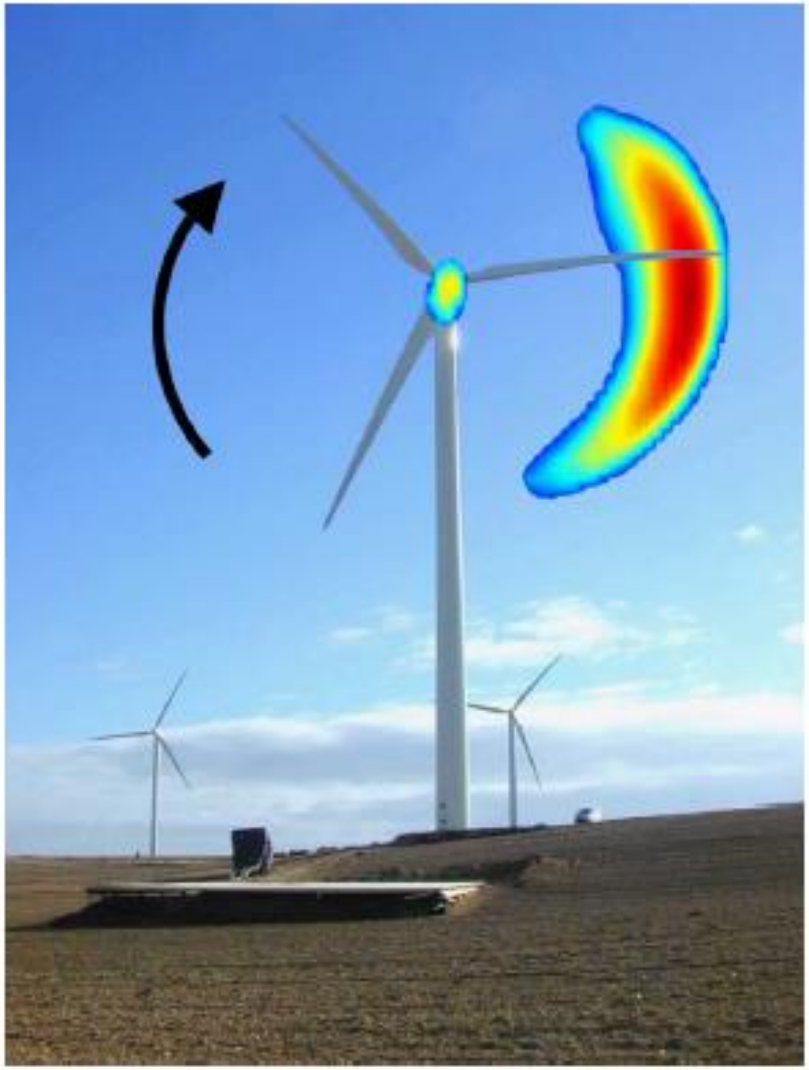

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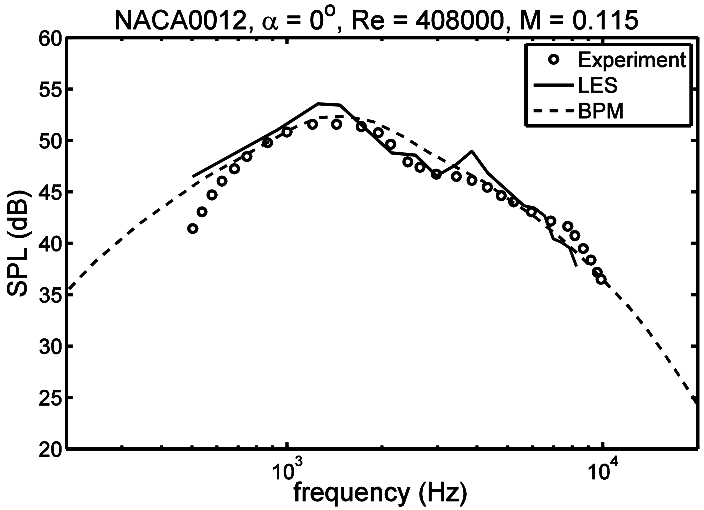
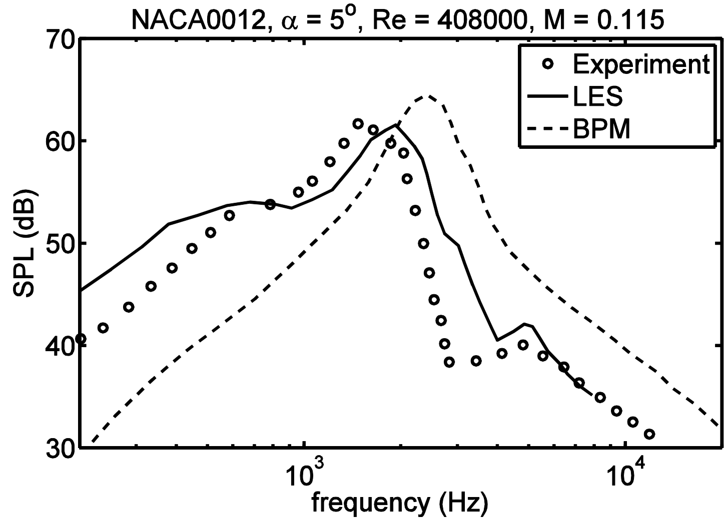
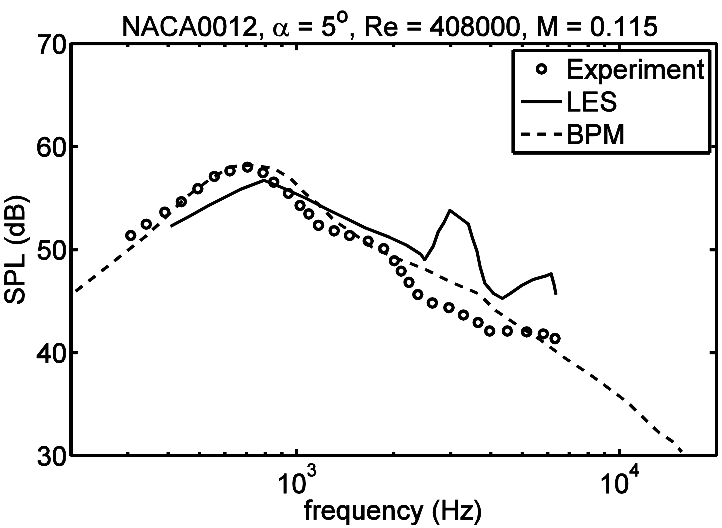
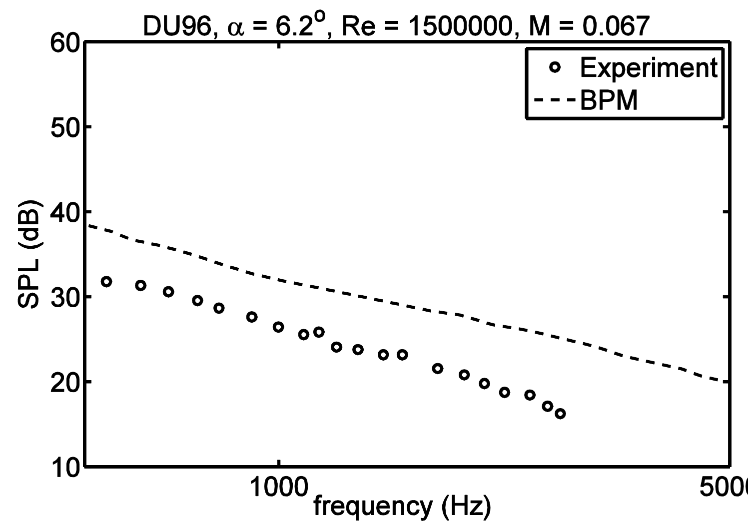
Engineering Models: BPM





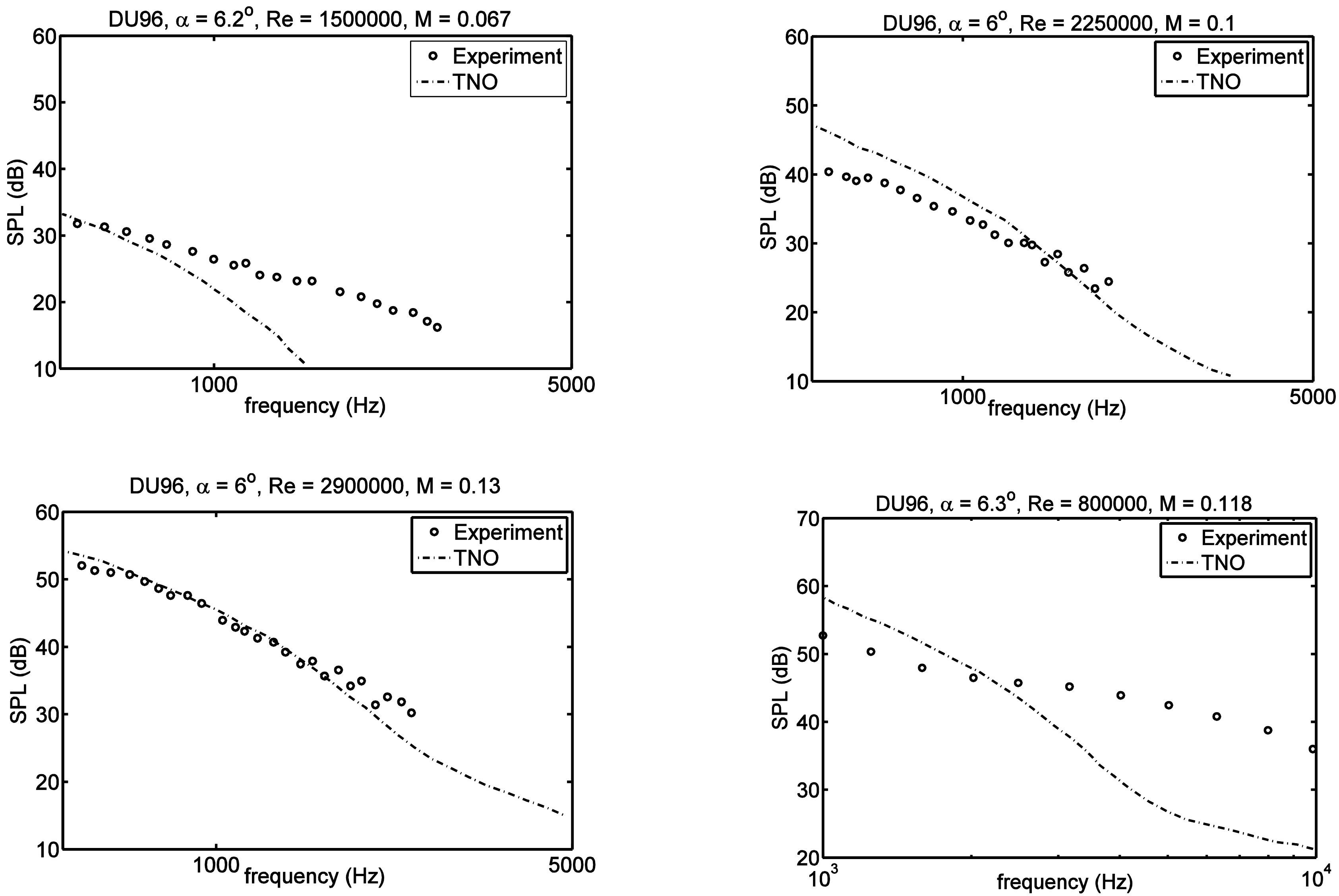




LES: Wolf *et al.*, 2012

Exp: Brooks *et al.*, 1989, Devenport *et al.*, 2010

Engineering Models: TNO



Exp: Devenport *et al.*, 2010, Herr and Pott-Pollenske, 2011

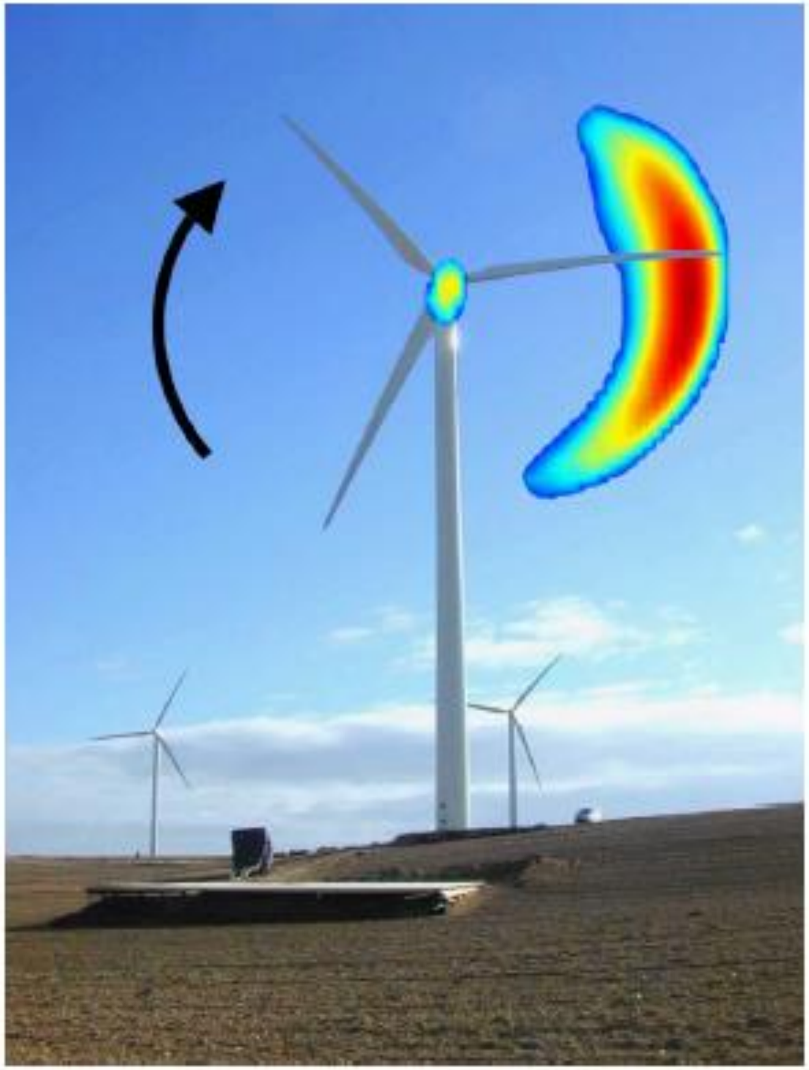
EUDP Project `Low Noise Airfoil' – Final Report

Author: BERTAGNOLIO Franck (Editor)
Title: EUDP Project `Low Noise Airfoil' - Final Report
Department: DTU Wind Energy

Report number:
DTU Wind Energy-E- 0004
Publication date:
June 2012

Finally, a new airfoil design was proposed based on a design concept including noise reduction. The new airfoil proved to perform better aerodynamically but noise reduction were not as important as expected, mainly due to the inaccuracy of the simplified flow model used in the design algorithm.

The need for HPC



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Numerical Simulation of Airfoil Self-Noise: Where are we?

- Significant progress in last 15 years
- Canonical configurations at low to moderate Reynolds numbers *routine*
- Full-scale Reynolds numbers challenging – Lack of synergy between experiments and simulations
- Non-canonical configurations – Stall Noise, Airfoil Tones etc poorly understood

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Wind turbine noise predictions: The challenge of high Reynolds number

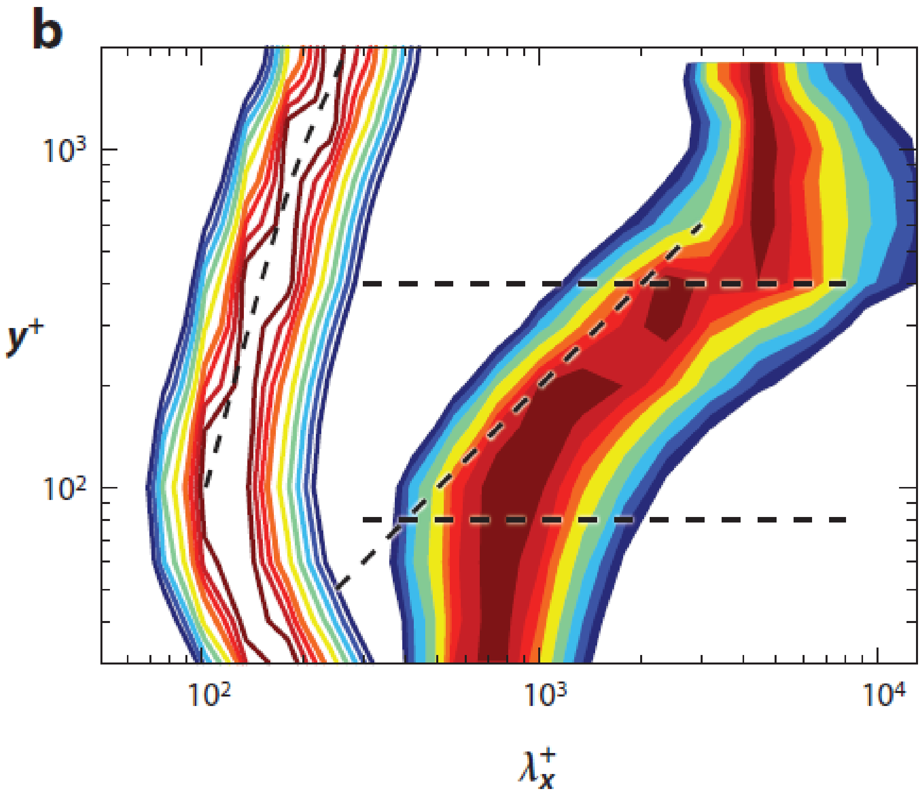
Contributors	Year	Configuration	Number of grid points
Wang *et al.* (LES)	2009	CD airfoil Re_c = **1.5 x 10^5**	~ 5 Million
Moon *et al.* (LES)	2010	Flat Plate Re_c = **1.3 x 10^5**	~ 3 Million
Winkler *et al.* (LES)	2012	NACA 6512-63 Re_c = **1.9 x 10^5**	~ 3 Million
Wolf *et al.* (LES)	2012	NACA 0012 Re_c = **4.08 x 10^5**	~ 54 Million
Jones and Sandberg (DNS)	2012	NACA 0012 with serrated TE Re_c = **5 x 10^4**	~ 170 Million
GE-Stanford Project	2012	DU96 Re_c = **1.5 x 10^6**	~127 – 180 Million

- WRLES of airfoil trailing edge noise restricted to low Reynolds numbers
- NREL 5MW offshore wind turbine – R = 63m, V = 9m/s, ω = 1.08rad/s, r = 7.55, Re(r = 3/4R) = **12x10^6**

R – rotor radius
V -wind speed
ω – rotation rate
r- tip speed ratio

Bazilevs et al., 2010

LES of a wall bounded turbulent flow – The challenge of high Reynolds number

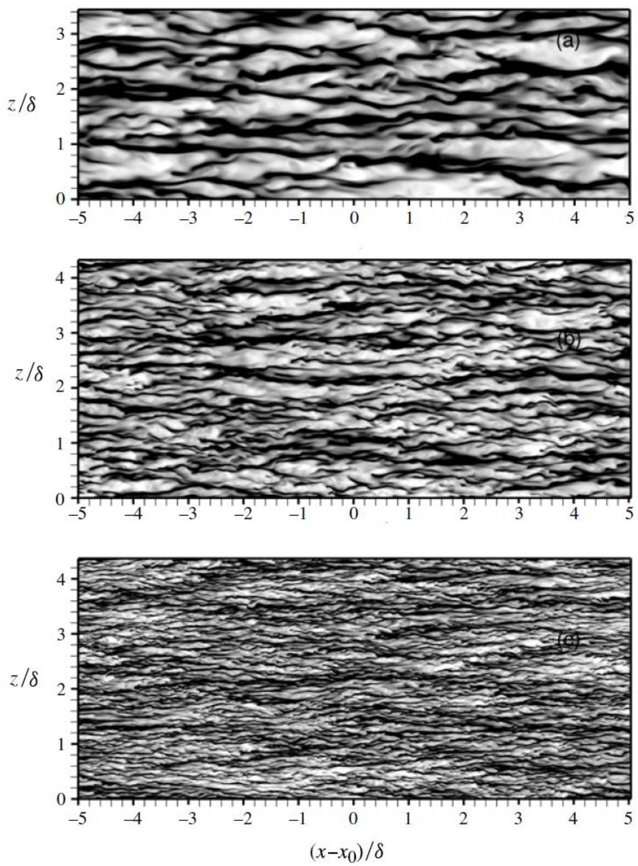


Filled contours – co-spectra of tangential Reynolds stress (production), Line contours – Spectra of vorticity magnitude (surrogate for dissipation). Results from DNS of turbulent channel flow at a friction Reynolds number of 2000

- Scale disparity between production and dissipation exists only away from the wall
- Wall Resolved LES grid needs to be very fine close to a wall
- Consequence - Number of grid points (N_g) α $Re_x^{13/7}$
- Wall Resolved LES is prohibitively expensive at large Reynolds numbers

Jimenez, 2012 Choi and Moin, 2012

Addressing the challenge of high Reynolds number



Instantaneous streamwise velocity from DNS of a turbulent boundary layer at $y^+ = 15$. Friction Reynolds numbers (top to bottom) - 251, 497, 1116

- The scale disparity between *outer* and *inner* scales responsible for $N_g \alpha Re_x^{13/7}$
- Remedy - *inner* scales not resolved
- Effect on *outer* scales modeled using a stress boundary condition
- *Outer* eddies scale with the local boundary layer thickness – weak dependence on Re_x
- Consequence - Number of grid points (N_g) α Re_x

Pirozzoli and Bernardini, 2011 Choi and Moin, 2012

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- Why Wall Modeled LES (WMLES)?
- WMLES Methodology
- WMLES of canonical flows
- WMLES of non-canonical flows
- WMLES of trailing edge noise at high Re
- WMLES of noise generated by an airfoil in near stall
- WMLES of flow past a wind turbine airfoil in the post stall regime
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WMLES methodology

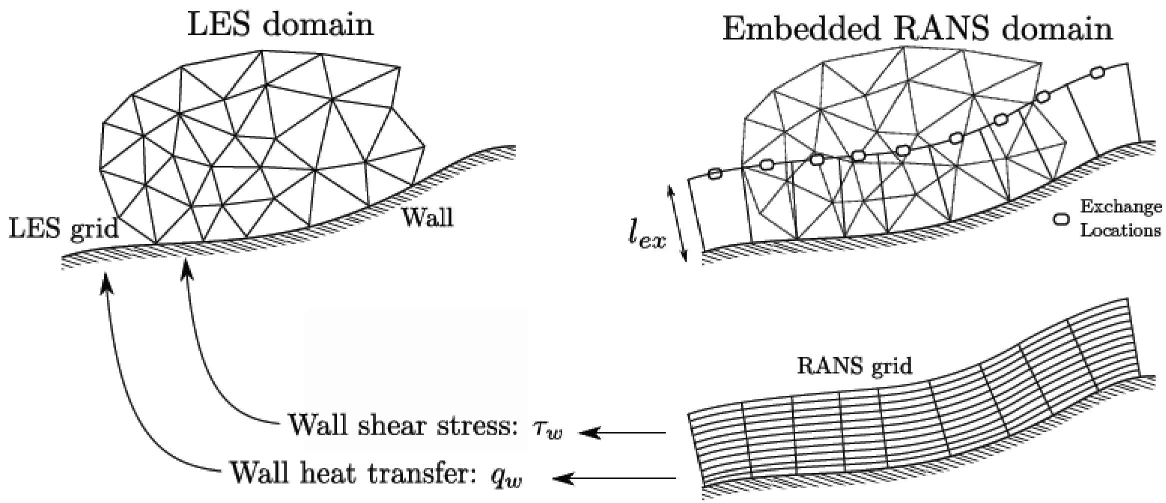

FIGURE 1. Sketch of the wall-modeling procedure.

- Compressible or *Weakly* Compressible Navier-Stokes equations with constant coefficient Vreman sub-grid scale model on the LES grid
- Time-independent ODEs in wall normal direction based on the equilibrium assumption and an algebraic eddy viscosity model with wall damping for turbulence on the RANS grid

Fig: Bodart and Larsson, 2011

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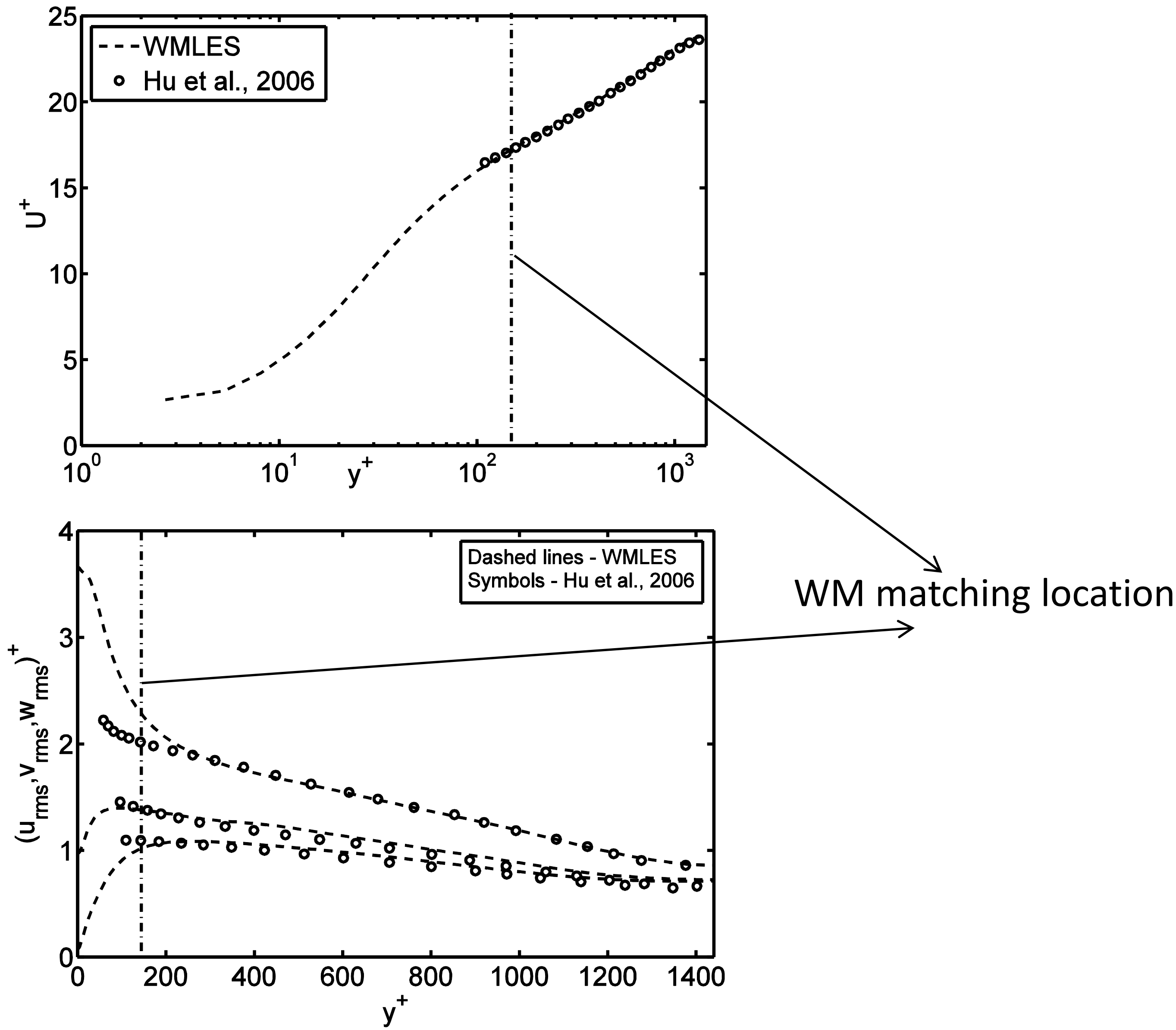
WMLES of turbulent channel flow

- Flow driven by a body force
- Periodic BCs in streamwise and spanwise directions
- Stress BC from wall model at the walls
- Results validated by comparison with DNS data
- Friction Reynolds number – 1440

WMLES of turbulent channel flow, $Re_\tau \sim 1440$, DNS ~ 500M points, WMLES ~ 1M points



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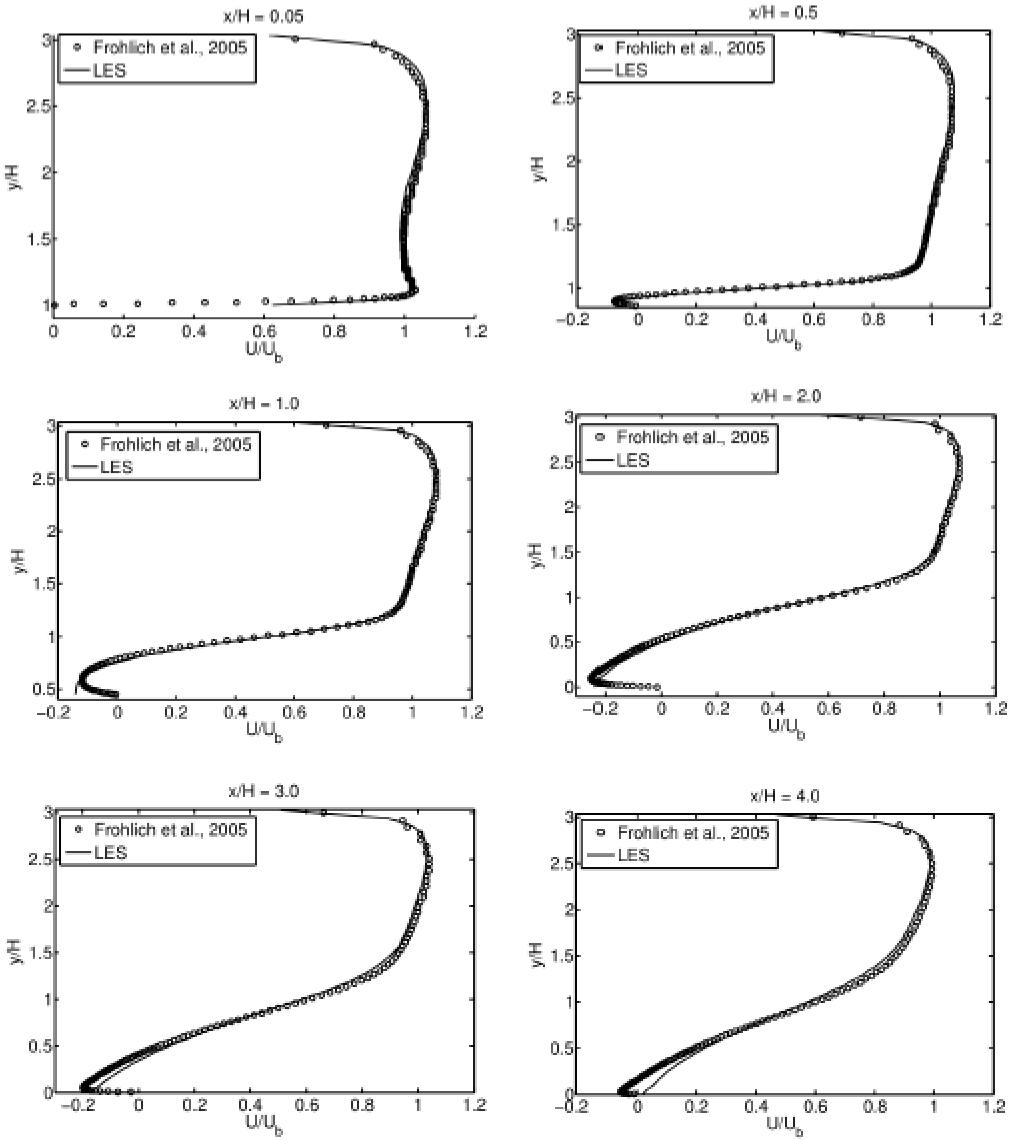
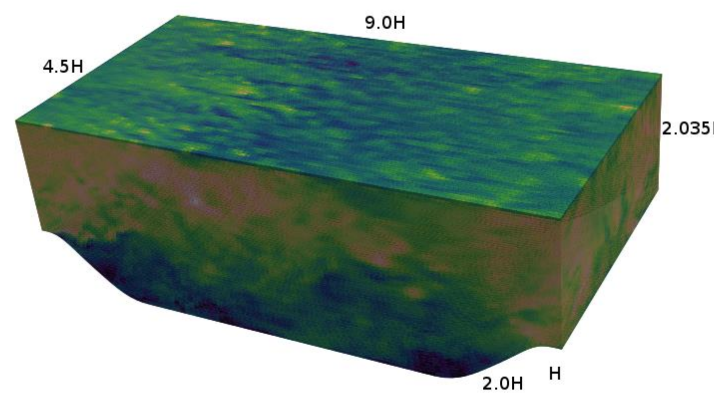
WMLES of separated flows



WMLES ~ 0.5M points
WRLES ~ 12M points
DNS ~ 200M points



Aerodynamic Aspects of Wind Energy Conversion

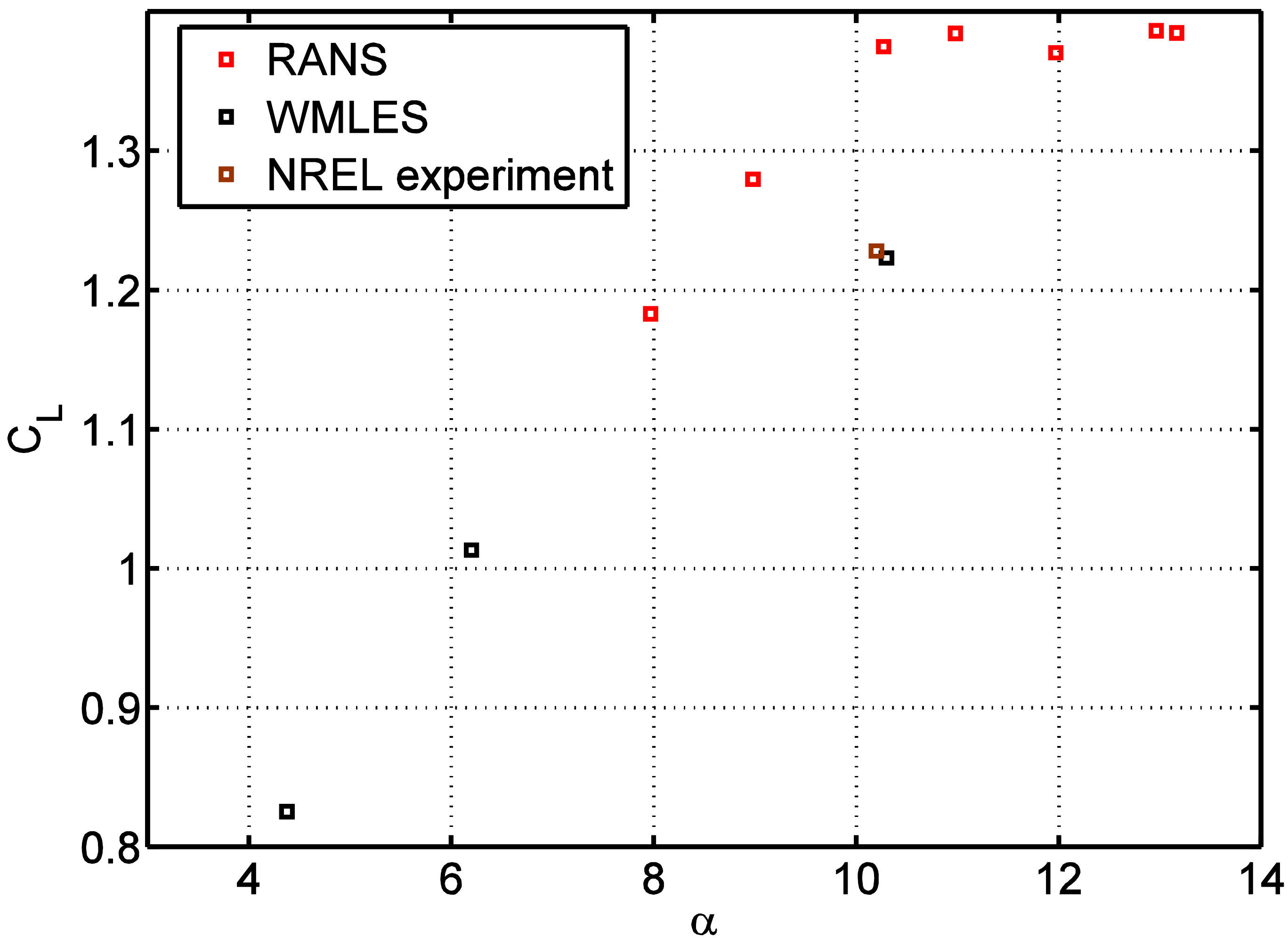
Jens Nørkær Sørensen

Department of Mechanical Engineering, Technical University of Denmark, DK-2800 Kongens Lyngby, Denmark; email: jns@mek.dtu.dk

Annu. Rev. Fluid Mech. 2011. 43:427–48

"The NREL experiments have achieved significant new insight into wind turbine aerodynamics and revealed serious shortcomings in present-day wind turbine aerodynamics prediction tools. The Navier-Stokes computations generally exhibited good agreement with the measurements up to wind speeds of approximately $10 ms^{-1}$. At this wind speed, flow separation sets in, and for higher wind speeds, the boundary layer characteristics are dominated by stall and the computations under-predict the power yield."

Predicting wind turbine stall using WMLES



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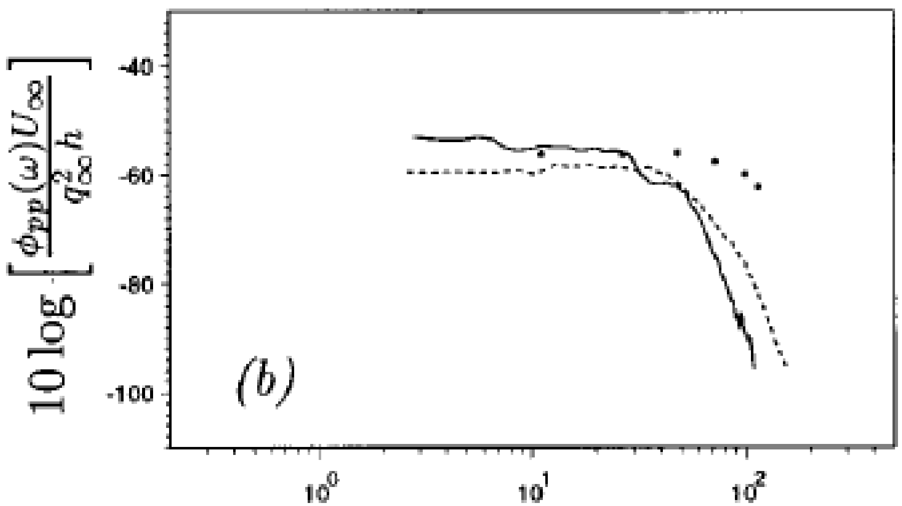
Over-prediction of fluctuating wall pressure and noise in WMLES

Dynamic wall modeling for large-eddy simulation of complex turbulent flows

Meng Wang[a] and Parviz Moin
Center for Turbulence Research, NASA Ames Research Center/Stanford University, MS 19-44, Moffett Field, California 94035

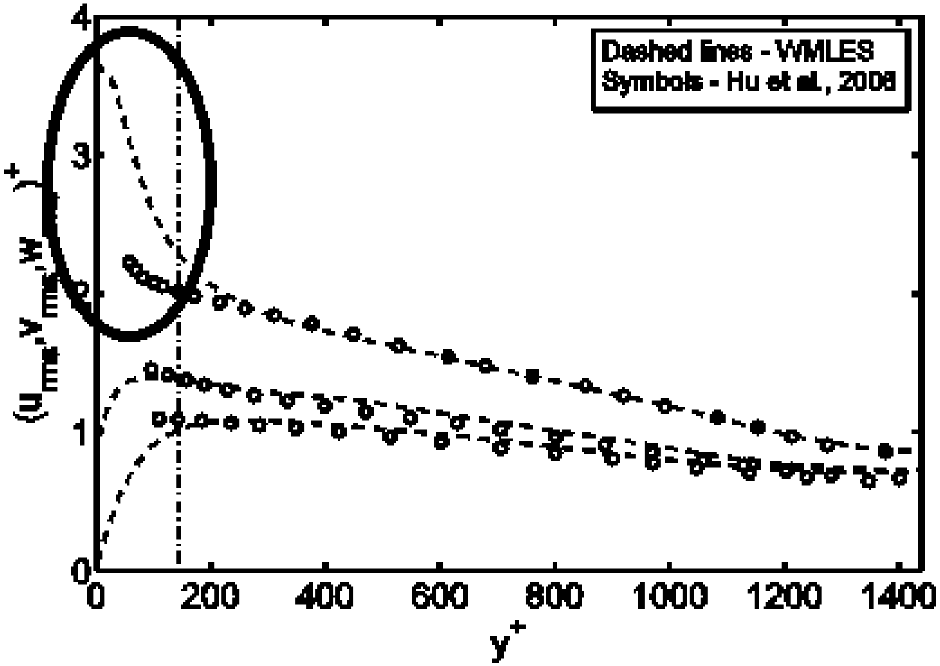
(Received 30 January 2001; accepted 18 March 2002; published 17 May 2002)



—— LES with TBLE wall model; ---- full LES

"Of particular interest in aeronautical and naval applications is the predictive capability of the method for surface pressure fluctuations and noise radiation. However, relative to the full LES spectra, the spectral levels are somewhat overpredicted, particularly in the attached flow region [Figs. 14(a)-14(c)]"

Over-prediction of turbulence intensity close to the wall

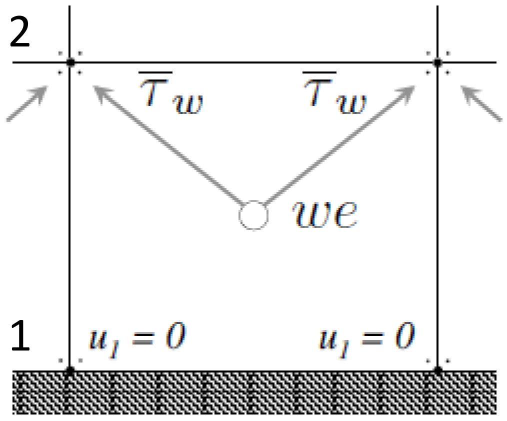


Results from WMLES of turbulent flow in a channel at a friction Reynolds number of 1440.

- What does the stress BC do to the structure of *attached* eddies close to the wall?
- Stress BC from wall model does not constrain tangential components of fluctuating velocity to vanish at the wall
- Attached eddies slosh at the wall

Townsend, 1976 Jimenez, 2012

How can it be fixed?



$\tau_w = (\mu + \mu_{sgs})\ (u_2 - u_1)/\Delta y$

Fig: Jaegle *et al.*, 2010

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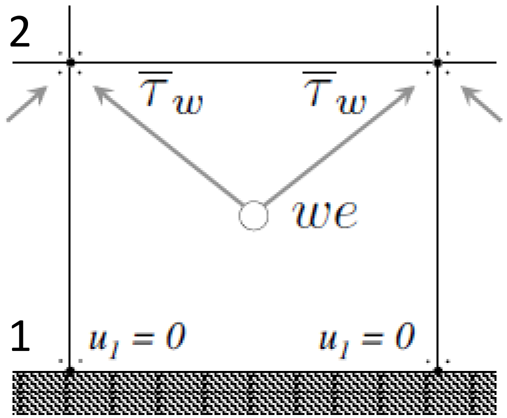
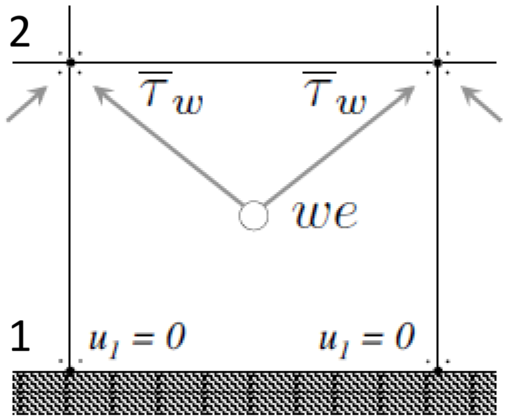


$\tau_w = (\mu + \mu_{sgs})\ (u_2 - 0)/\Delta y$

Fig: Jaegle *et al.*, 2010

How can it be fixed?



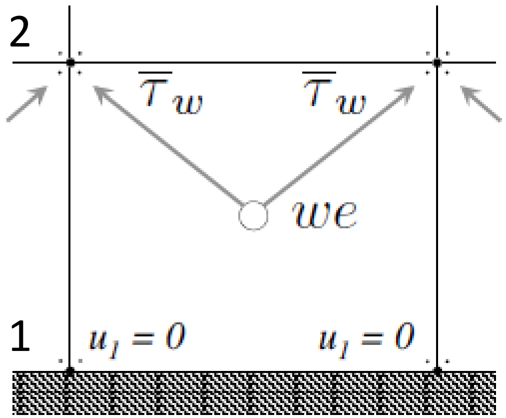
$$\tau_w = (\mu + \mu_{sgs})\ (u_2 - 0)/\Delta y$$

μ_t

Augment μ_t to enforce the shear stress from the wall model

Fig: Jaegle *et al.*, 2010

How can it be fixed?



$$\tau_w = (\mu + \mu_{sgs})\ (u_2 - 0)/\Delta y$$

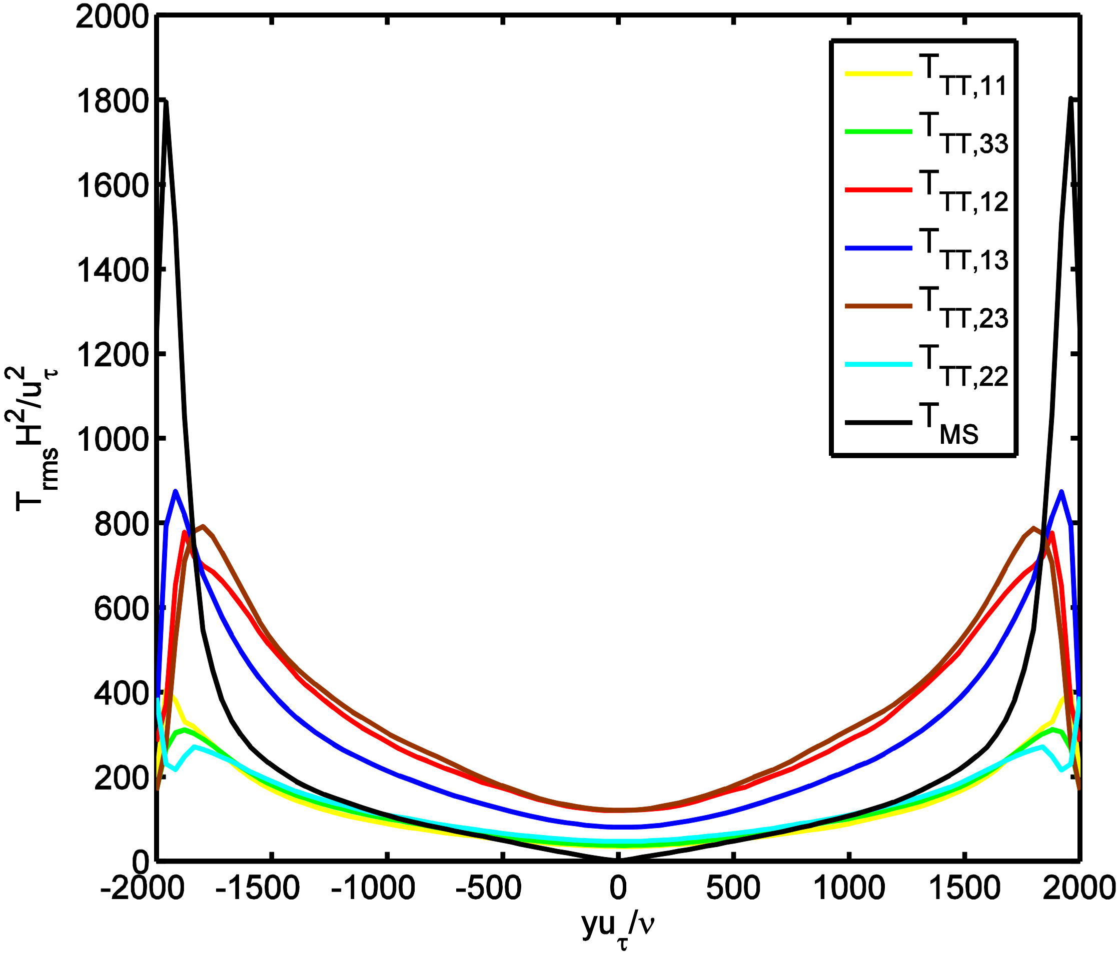
μ_t

Augment μ_t to enforce the shear stress from the wall model

- *No slip* enforced at the wall
- Viscosity artificially augmented at the wall to enforce the shear stress from the wall model
- Does it improve prediction of fluctuating wall pressure? Yes
- Does it fix the issue altogether? Not quite

Fig: Jaegle *et al.*, 2010

Budget of Poisson equation for fluctuating pressure



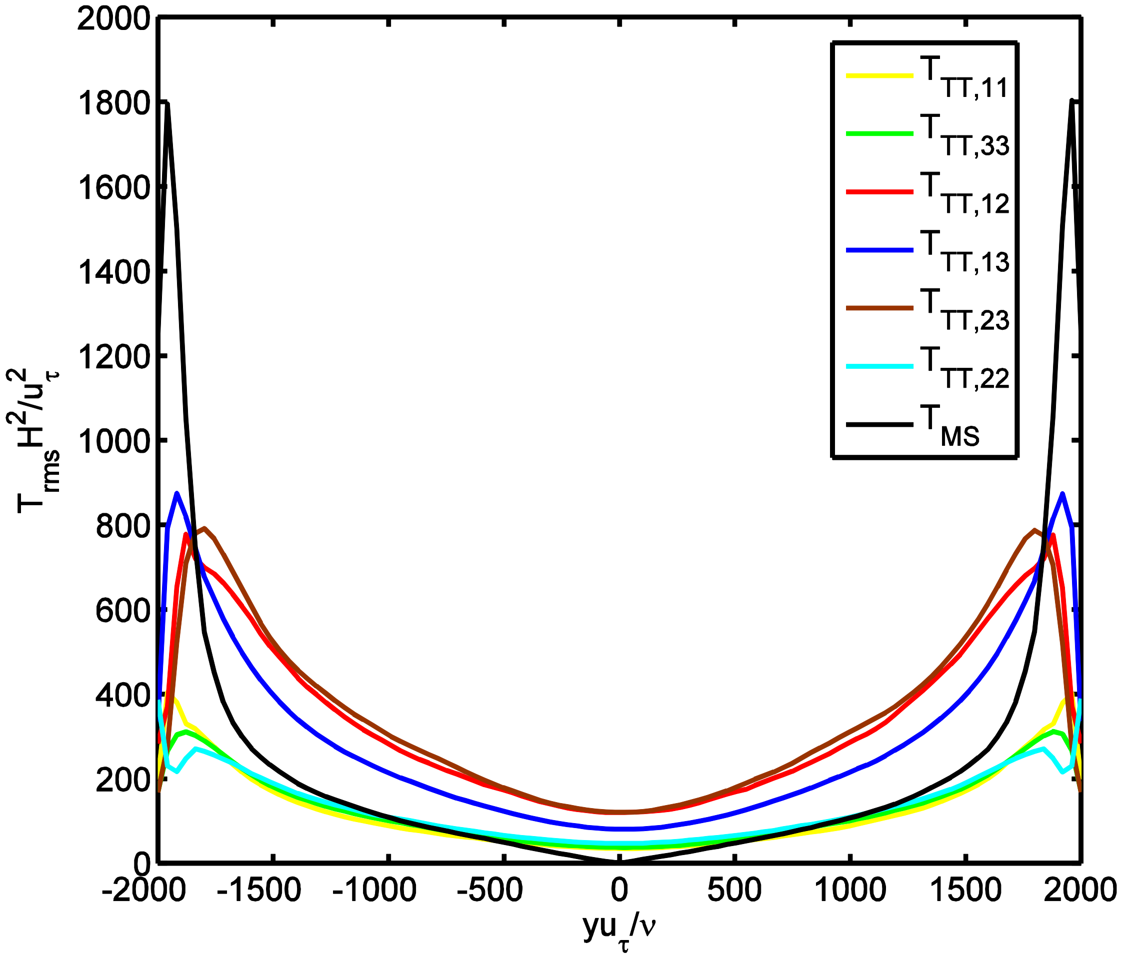
From WMLES of turbulent flow in a channel at a friction Reynolds number of 2000.

$$\frac{\partial^2 p}{\partial x_i \partial x_i} = -\{T^{\mathrm{MS}} + T^{\mathrm{TT}}\}$$

$$T^{\mathrm{MS}} = 2\,\frac{\partial U}{\partial y}\,\frac{\partial v}{\partial x}$$

- Turbulence-mean shear interaction (Rapid) term over-predicted close to the wall

Budget of Poisson equation for fluctuating pressure



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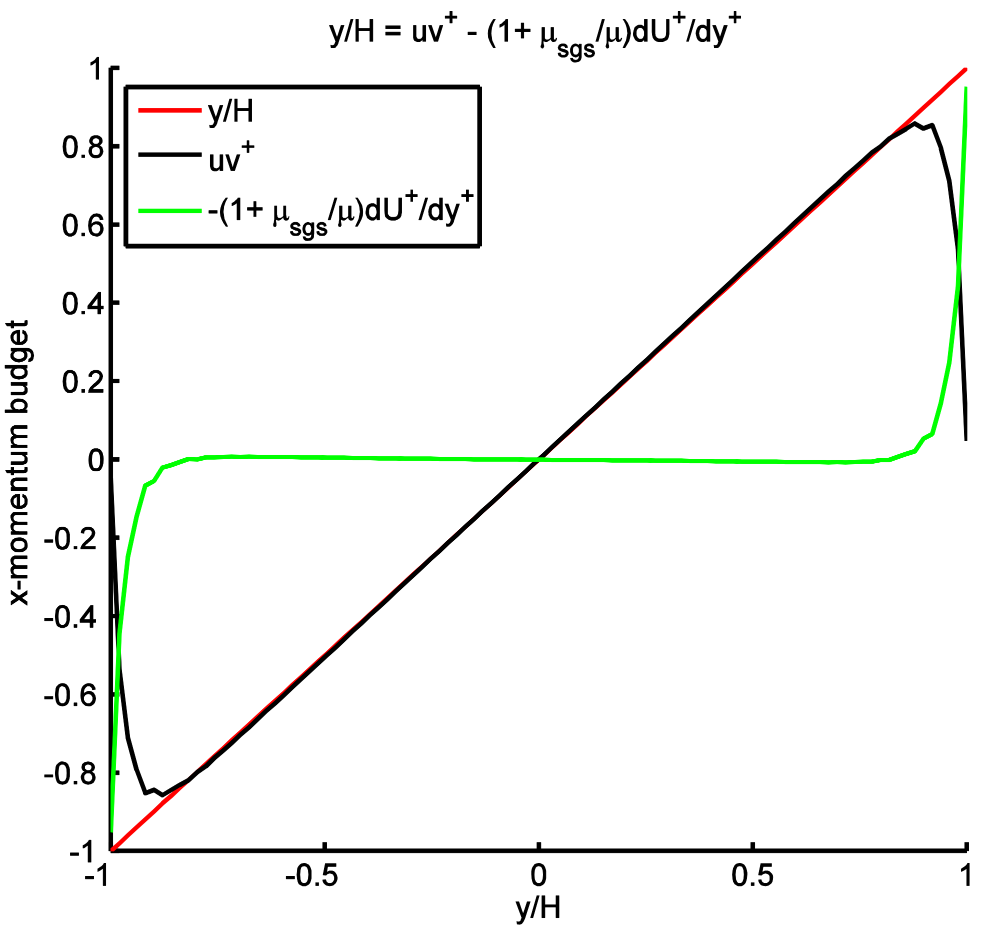
- Turbulence-mean shear interaction (Rapid) term over-predicted close to the wall
- Why?

Mean x-momentum balance



From WMLES of turbulent flow in a channel at a friction Reynolds number of 2000.

- Reynolds shear stress under-predicted close to the wall
- Subgrid scale model does not contribute *enough* (Not a RANS model)
- Flux from the wall sustained through a higher value of mean velocity gradient

Can the error be fixed? How does it respond to grid refinement?

- To solve the issue, numerical and subgrid scale model errors at the first few off-wall points need to be addressed – Even a *perfect* wall stress model won't suffice

- A posteriori correction possible, but not practical

- The over-prediction reduces on finer grids as the Reynolds shear stress starts contributes more to the momentum balance in the vicinity of the wall

Trailing edge noise predictions at full-scale Reynolds number: The BANC workshop

Configuration	**Airfoil**	**AoA**	**Reynolds Number**	**Mach Number**	**Transition location**
BANC 1	NACA0012	0^o	1.50M	0.1664	0.065c
BANC 2	NACA0012	4^o	1.50M	0.1641	0.065c
BANC 3	NACA0012	6^o	1.50M	0.1597	0.060c/0.070c (SS/PS)
BANC 4	NACA0012	0^o	1.00M	0.1118	0.065c
BANC 5	DU96	4^o	1.13M	0.1730	0.12c/0.15c (SS/PS)

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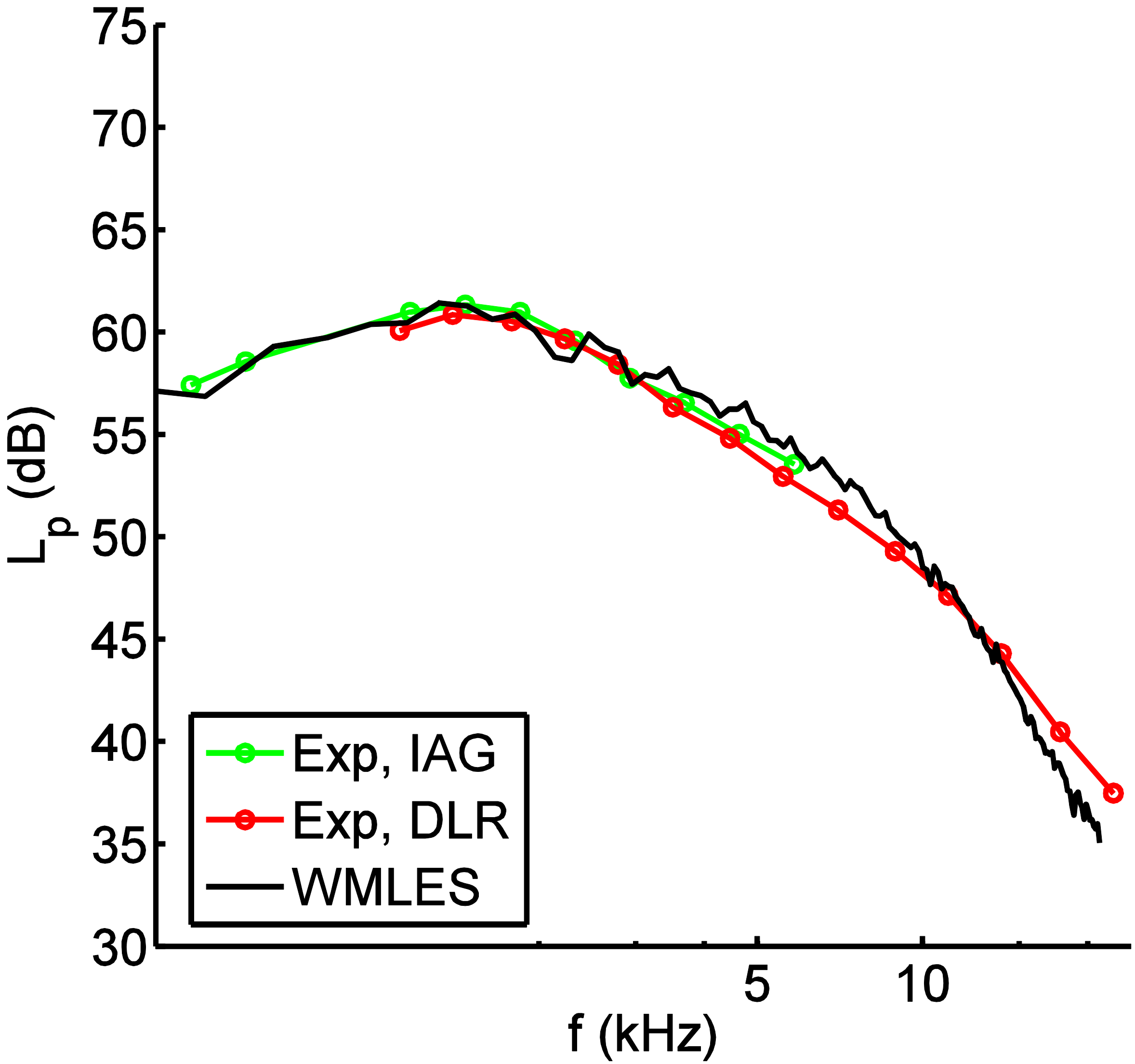
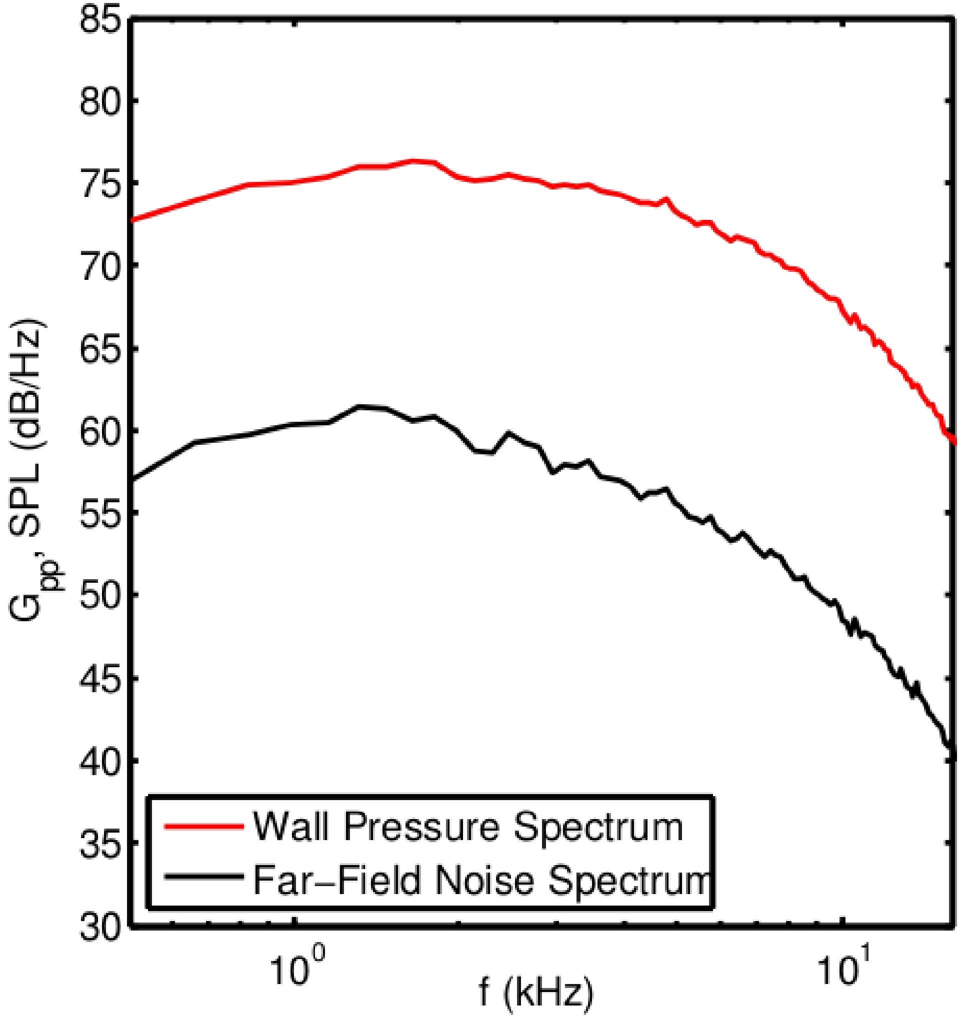
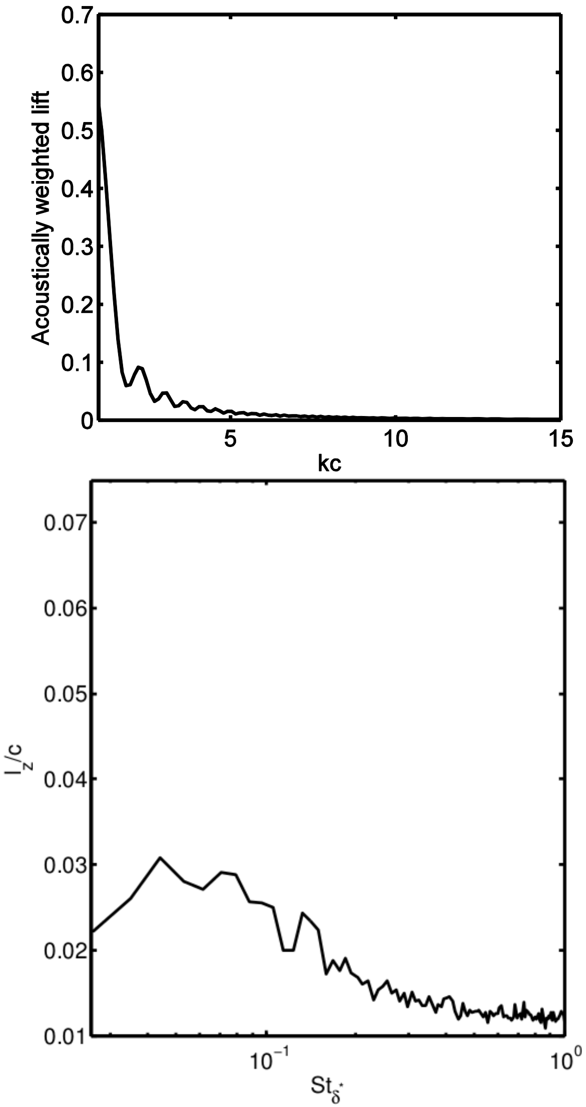
BANC 1 - NACA 0012, Re = 1.5M, M = 0.1664, AoA = 0°

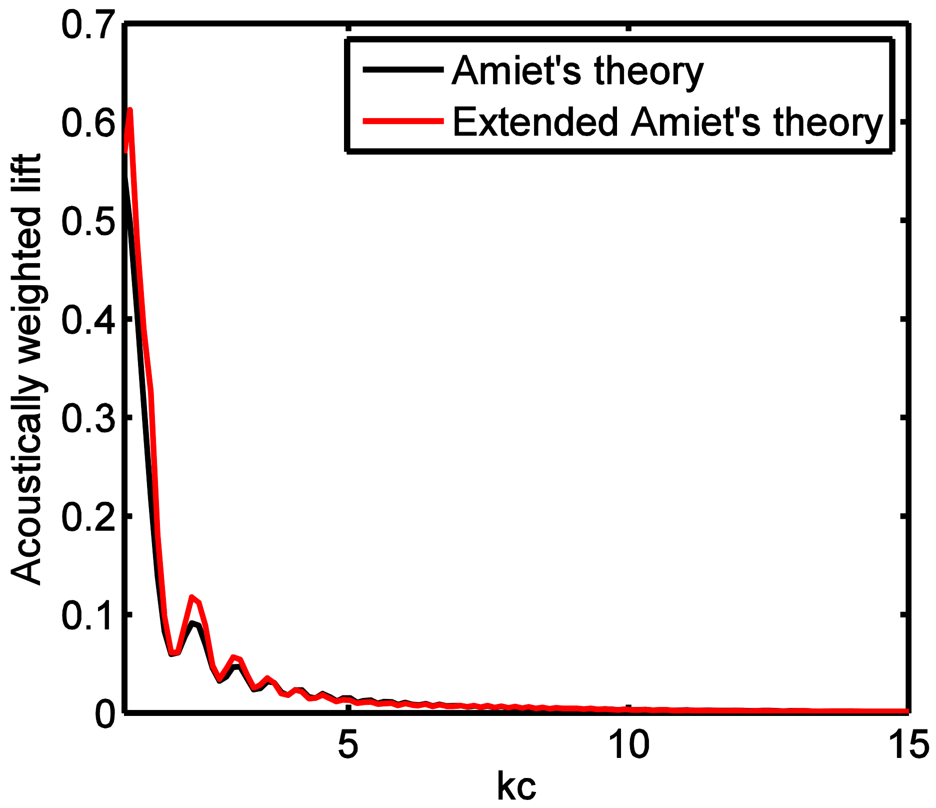


Interpreting the far-field noise spectrum





Is leading edge back-scattering important?



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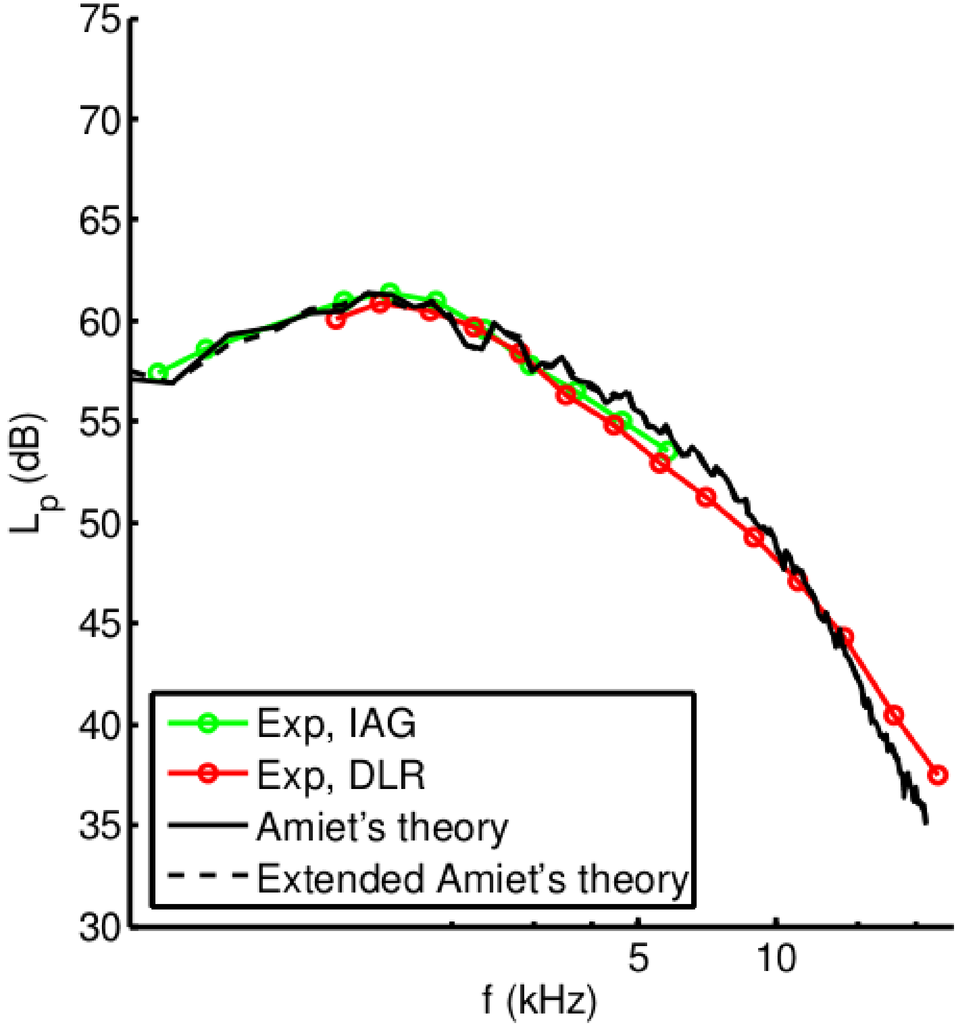
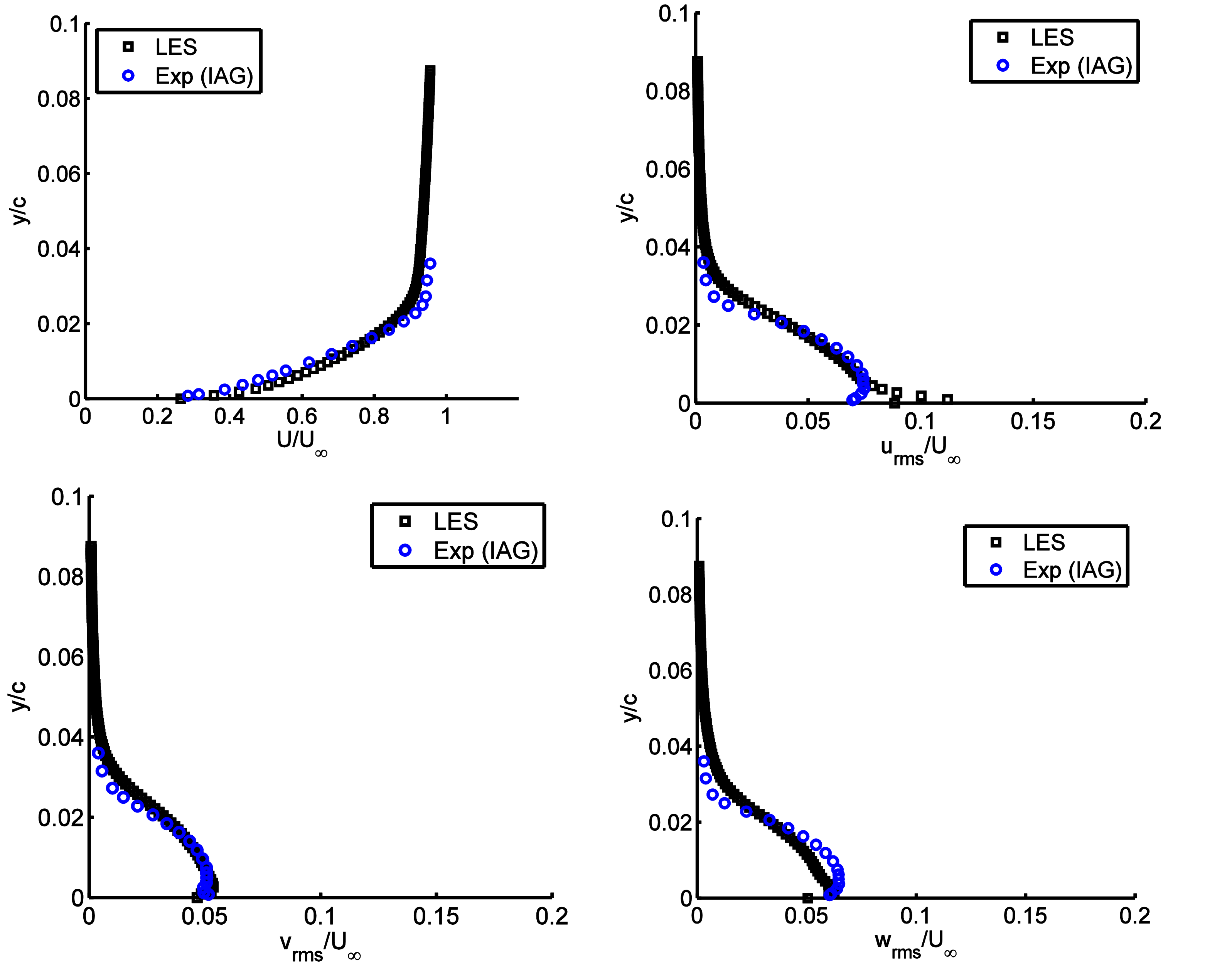
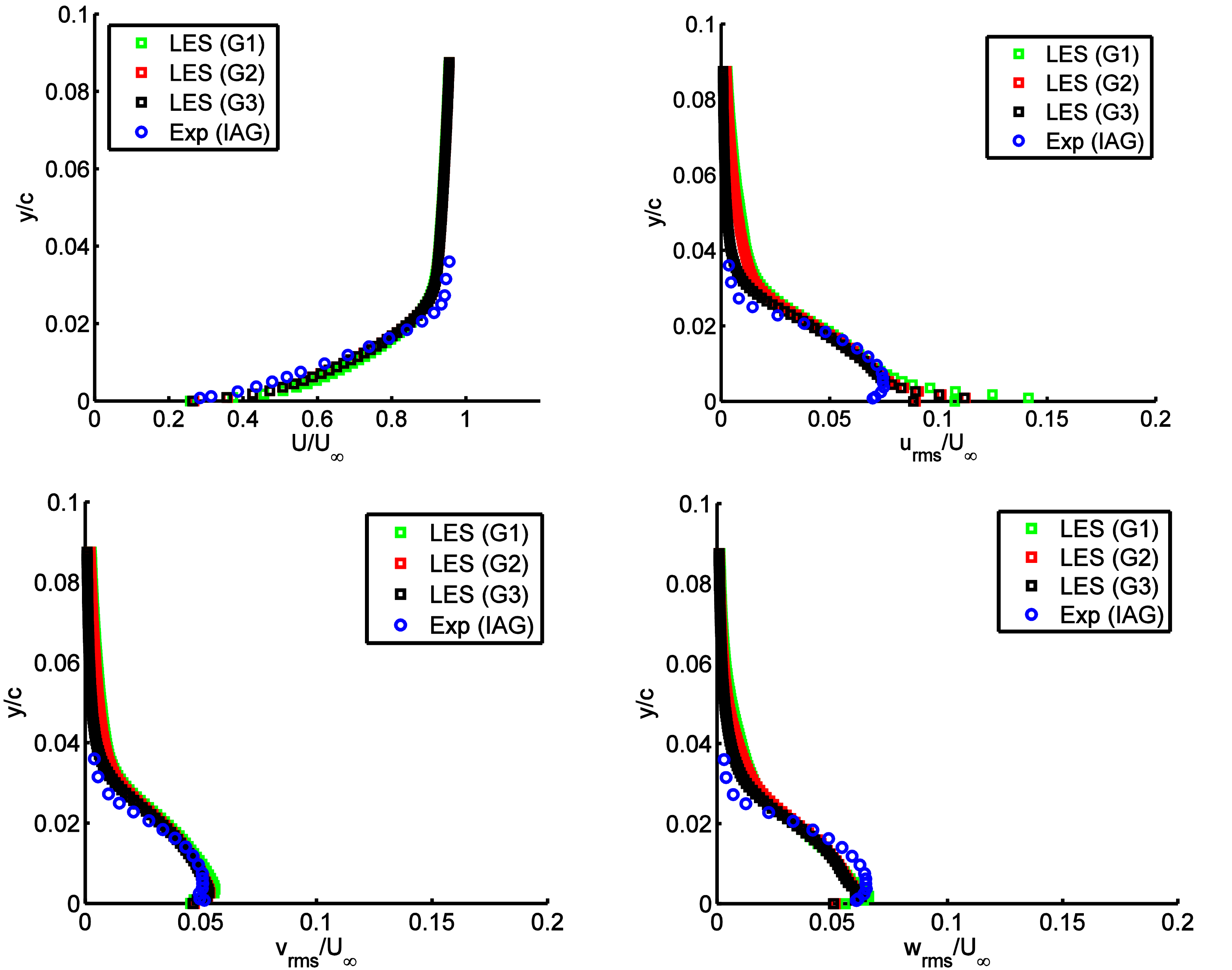


Comparison of near wake flow-field to measurements



Sensitivity to grid resolution



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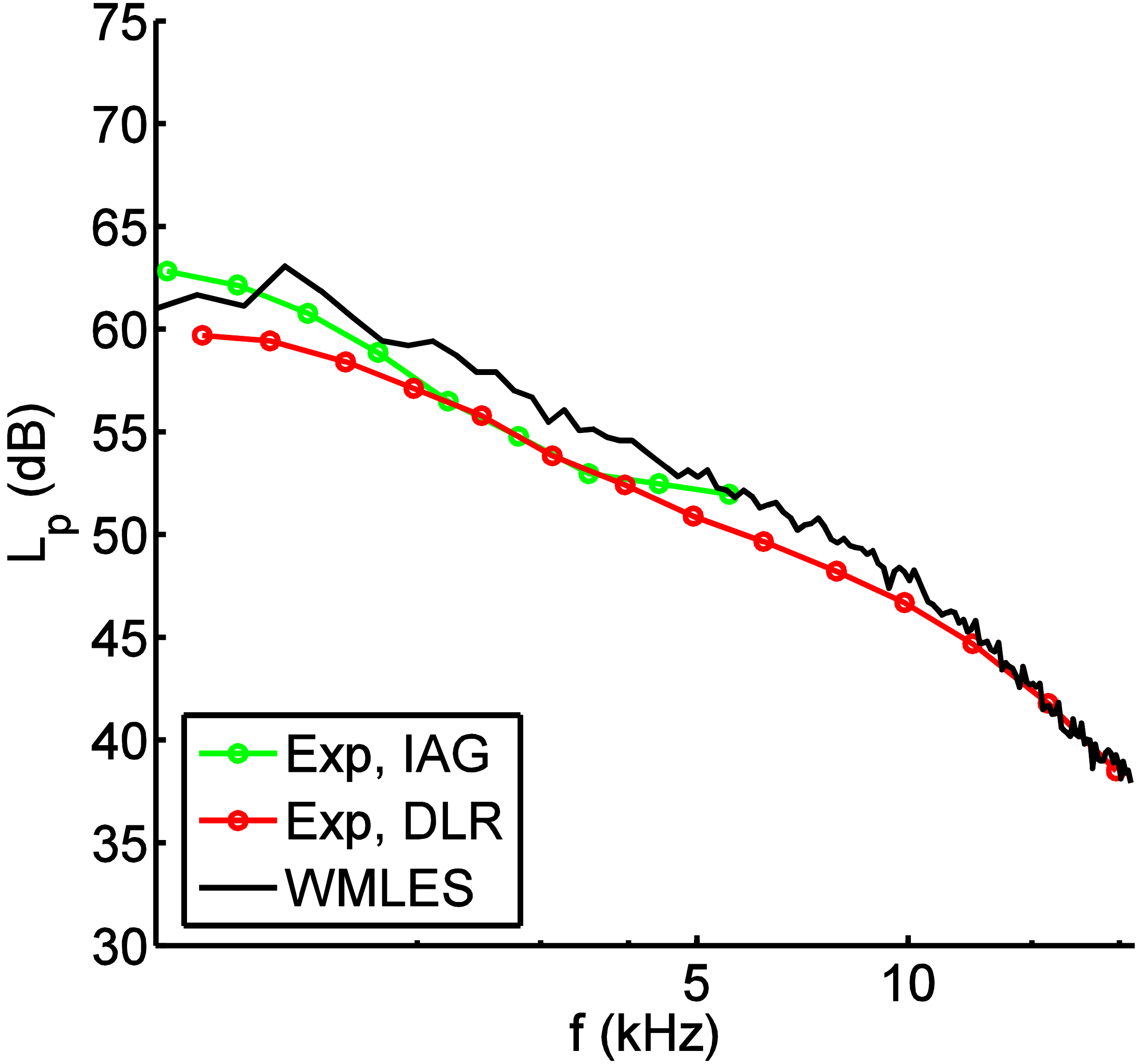
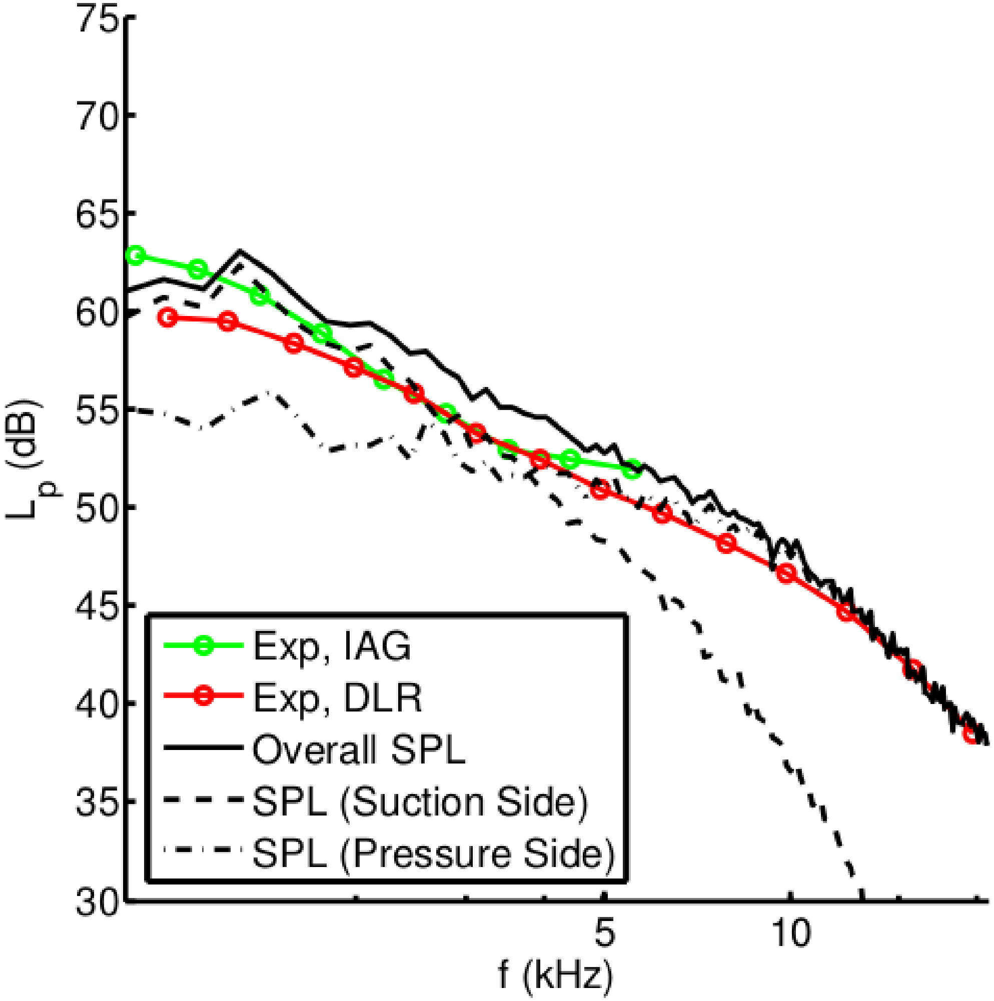
BANC 5	DU96	4^o	1.13M	0.1730	0.12c/0.15c (SS/PS)

BANC 3 - NACA 0012, Re = 1.5M, M = 0.1597, AoA = 6°



The effect of loading



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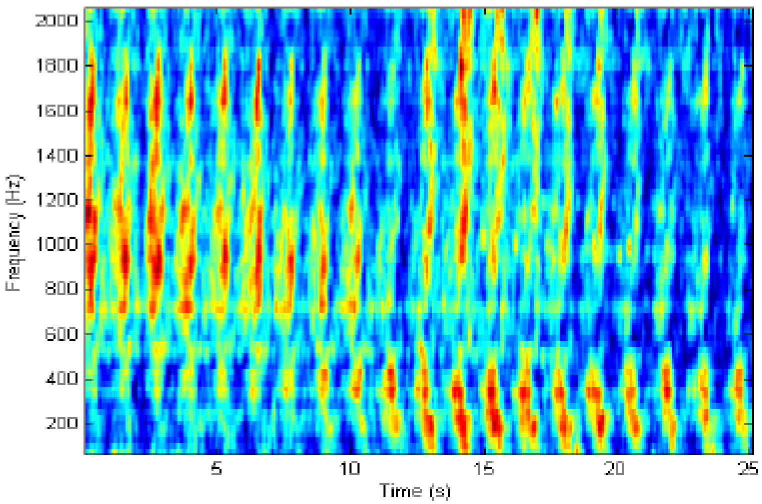
Motivation: *Other* Amplitude modulation (OAM) of wind turbine noise

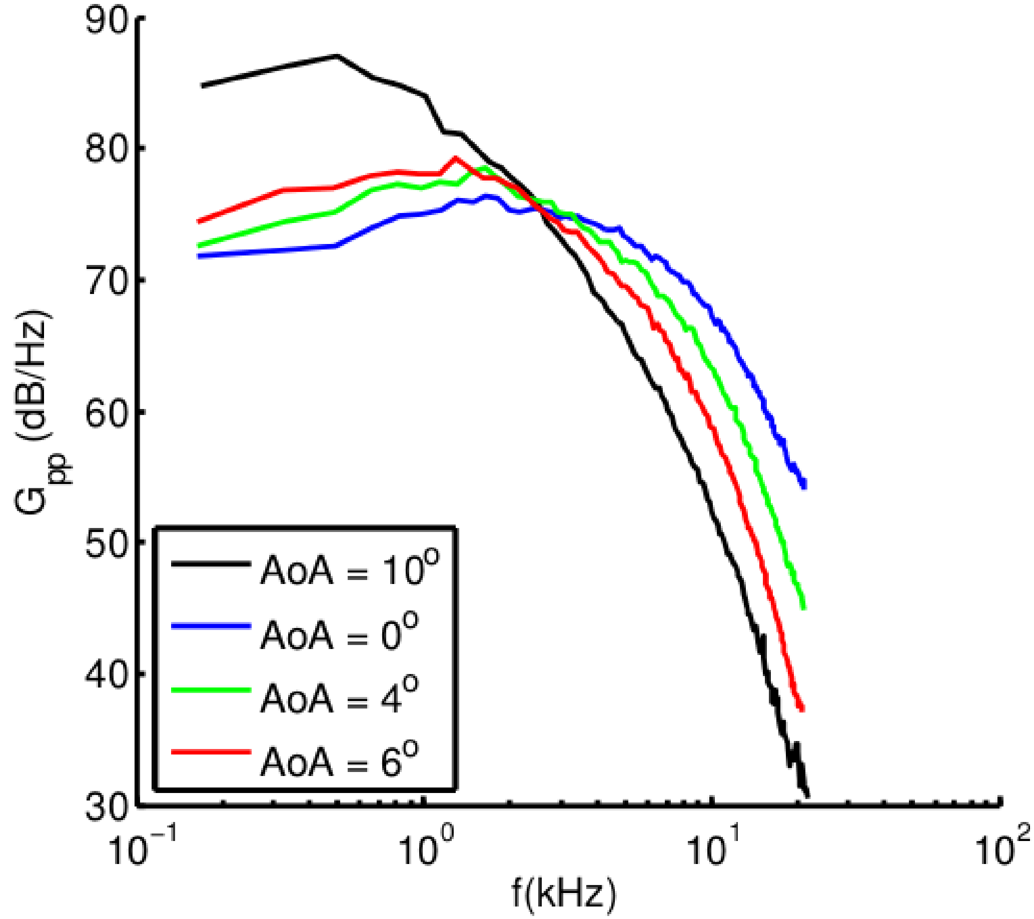


Spectrogram of wind turbine noise shows intense, intermittent, *thumping* noise believed to caused by dynamic stall of wind turbine blades.

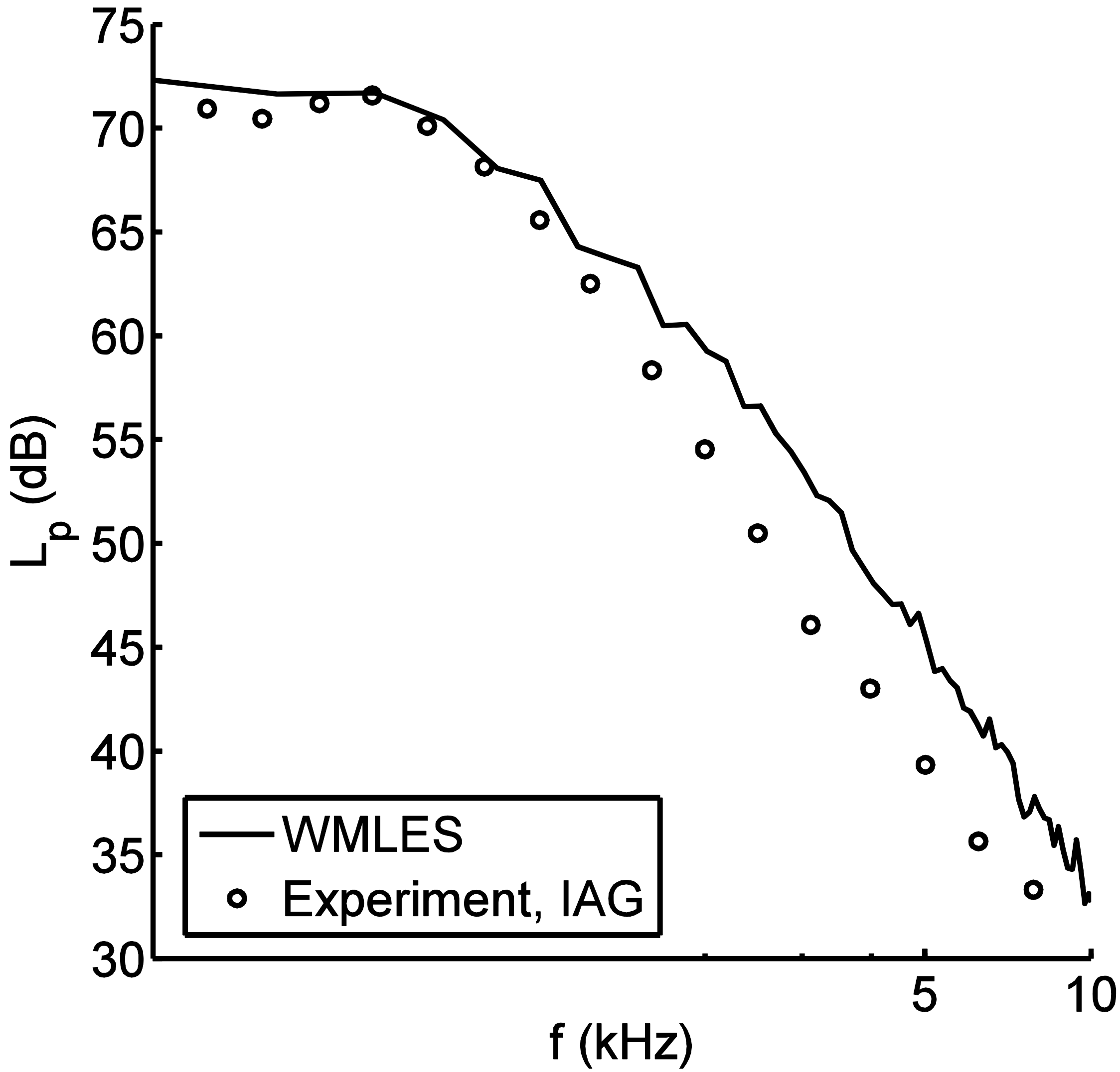
- High levels of amplitude modulation (AM) at large distances *downwind* or *upwind*
- Level and *character* of AM altered
- Increase in low-frequency content
- Enhanced modulation depth
- *Transient* , *dynamic* stall believed to be responsible
- Stall noise prediction – a pacing item (Laratro *et al*., 2014)

Fig: Smith *et al*., 2012 RenewableUK, 2013 Laratro *et al*., 2014

What happens to fluctuating wall pressure at higher AoA?



Noise generated by an airfoil in *near* stall configuration – NACA 0012, Re = 1.5M, M = 0.16, AoA = 10^{o}



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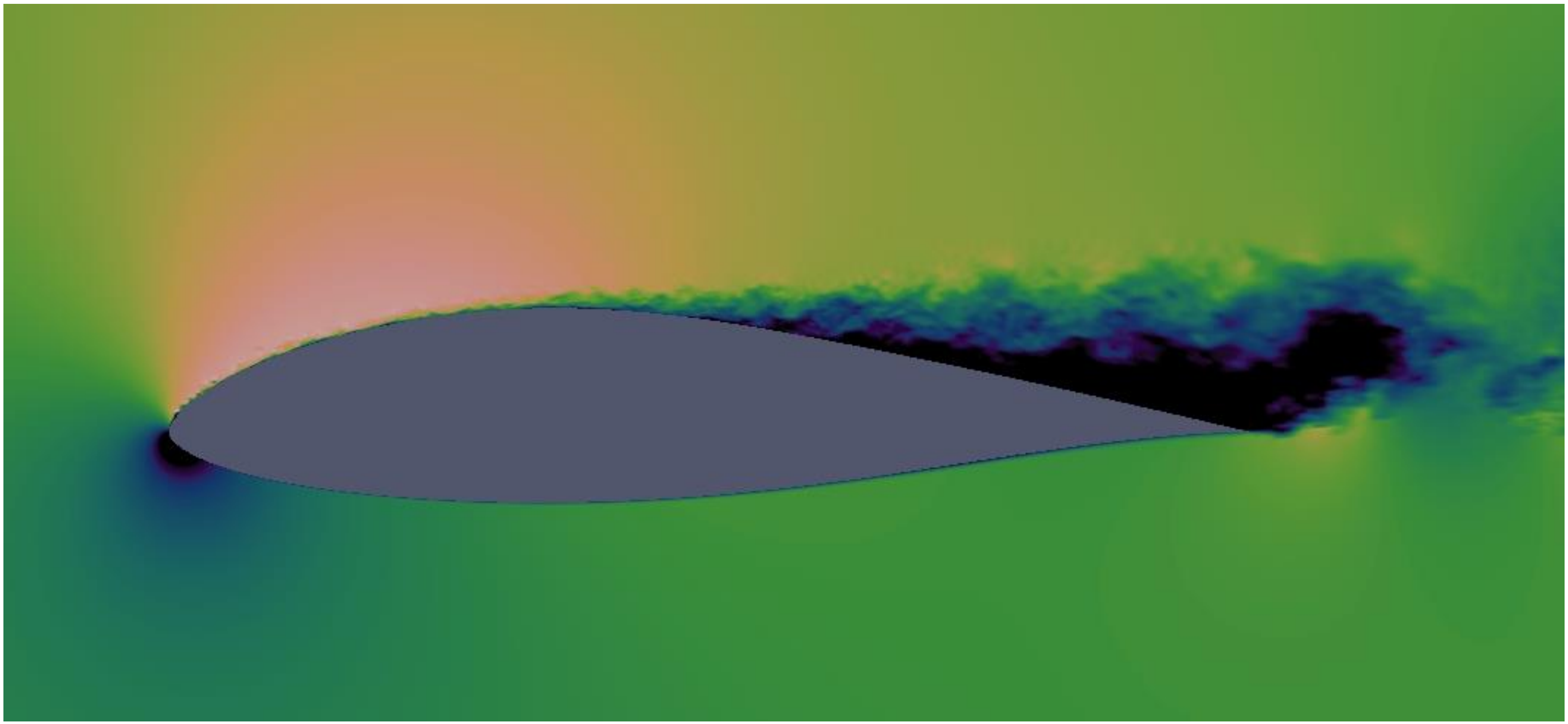
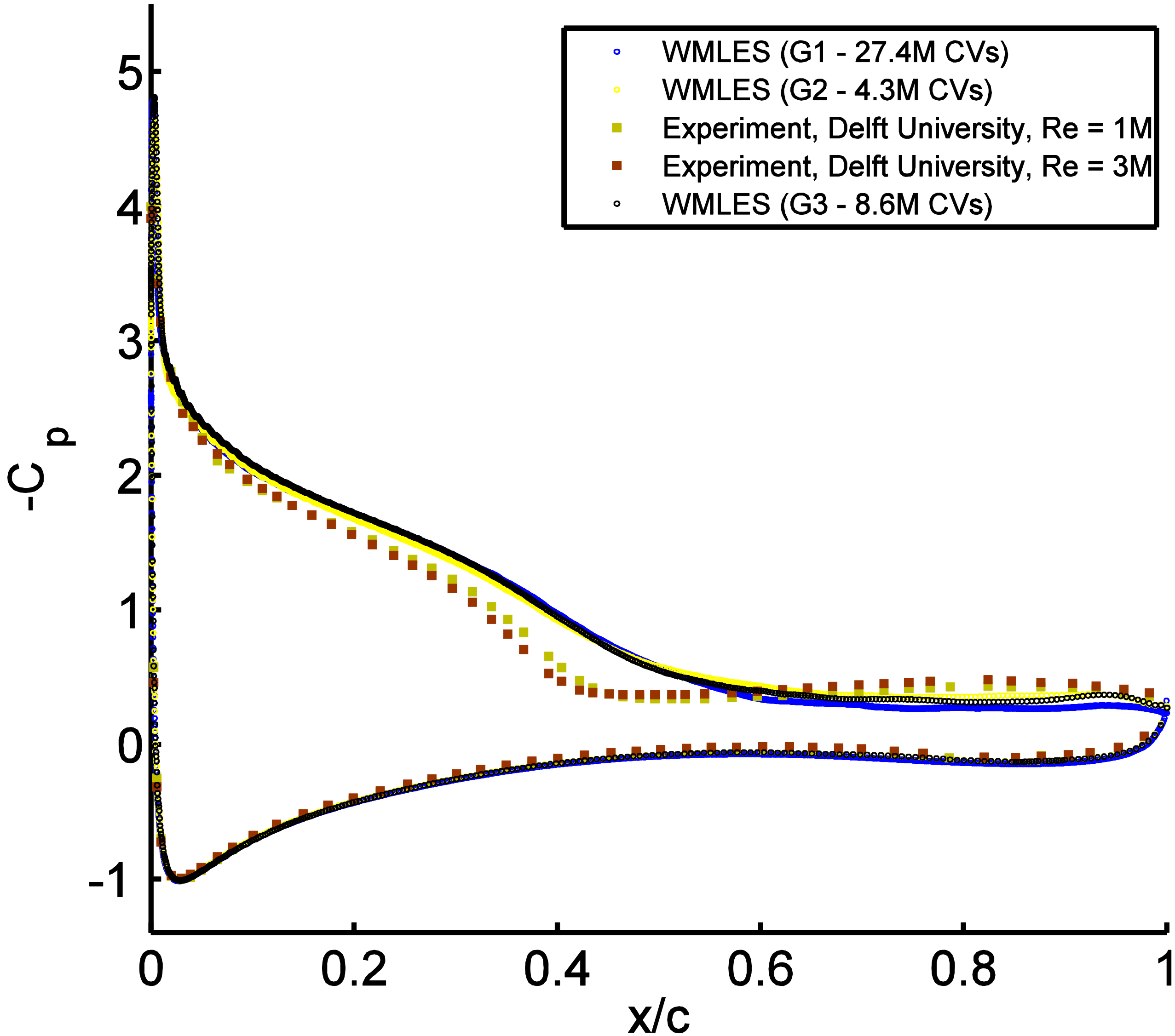
WMLES of turbulent flow past a DU96 airfoil in stall

- Configuration – DU96-W-180 airfoil at an angle of attack of 13.2 degrees, chord based Reynolds number of 1.5M
- Comparisons made with experiments from Delft University (Courtesy: Dr. N. Timmer)

Flow Visualization: Contours of streamwise velocity (Negative values intentionally saturated to visualize reverse flow regions better)



Comparison with Experiments

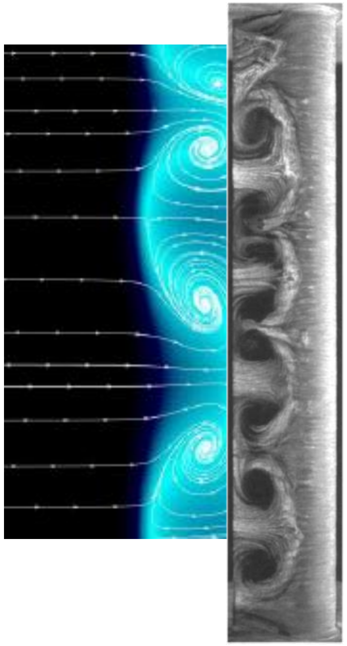


Motivation for large span calculation

Dataset	Lift Coefficient
WMLES	**1.22+/-0.01***
Delft (Re = 1M, AoA = 13.625)	1.109
Delft (Re = 2M, AoA = 13.13)	1.12
Delft (Re = 3M, AoA = 13.62)	1.105
RANS (Re = 1.5M, AoA = 13.2)	1.3915

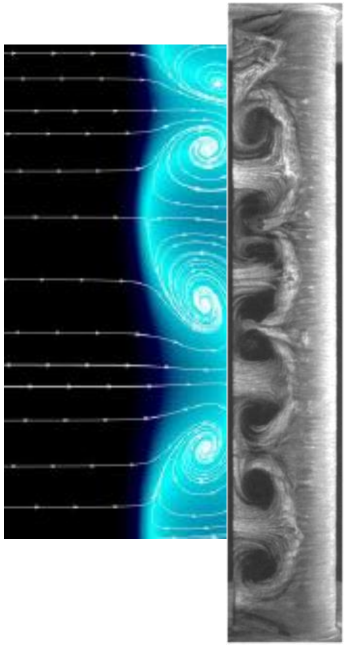
- **WMLES over-predicts lift by 10%**
- RANS over-predicts lift by 25%

*From calculations done on three different grids



- Are large-scale 3D flow instabilities important?
- Are large-span calculations *without* end-wall effects useful?

Figs: F. Menter, *private communication* and Schewe, 2001



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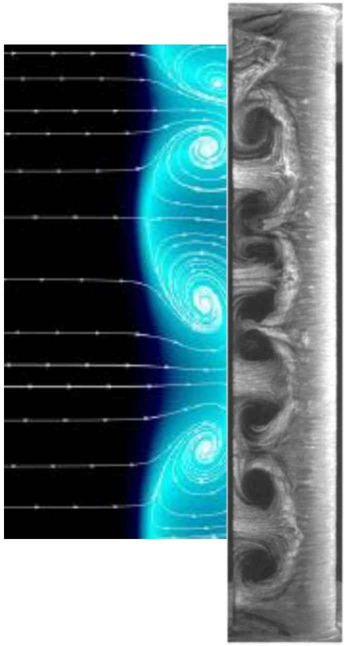
- Yes – Stall cells affected by end-walls, but *not* caused by it (cf. Spalart (2014))

Figs: F. Menter, *private communication* and Schewe, 2001



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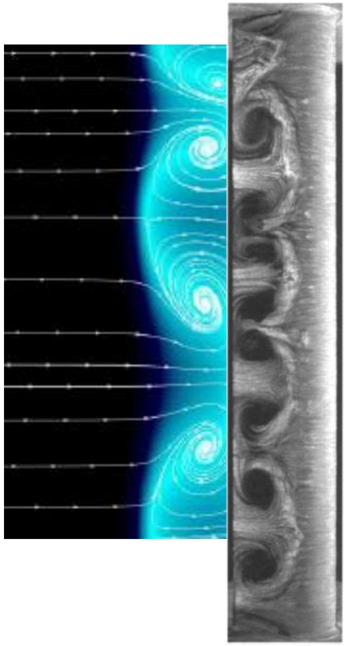
Grid	Domain size	Grid points
G1	20Cx20Cx0.12C	~27.4M
G2	20Cx20Cx0.12C	~4.3M
G3	20Cx20Cx0.12C	~8.6M
G4	20Cx20Cx1.2C	~40.5M

Figs: F. Menter, *private communication* and Schewe, 2001



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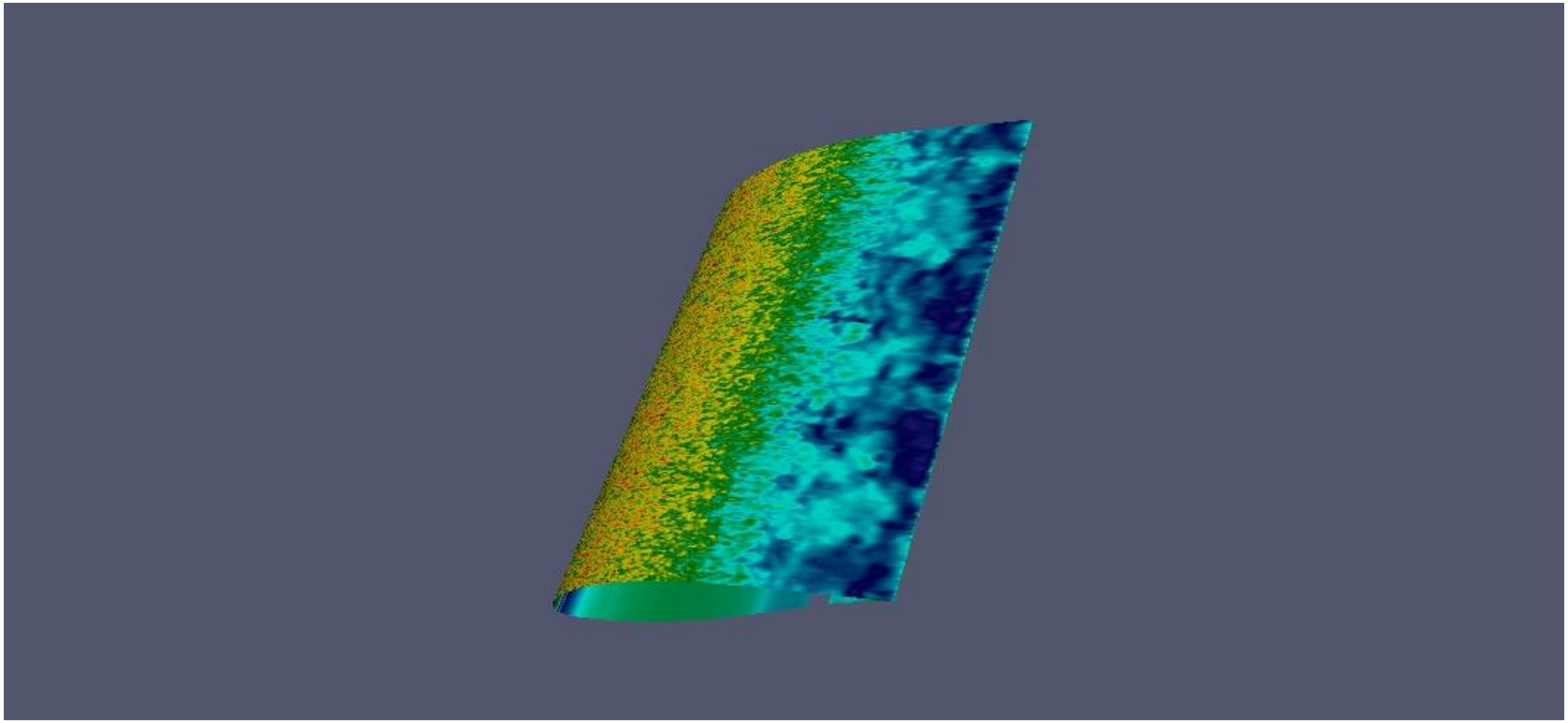
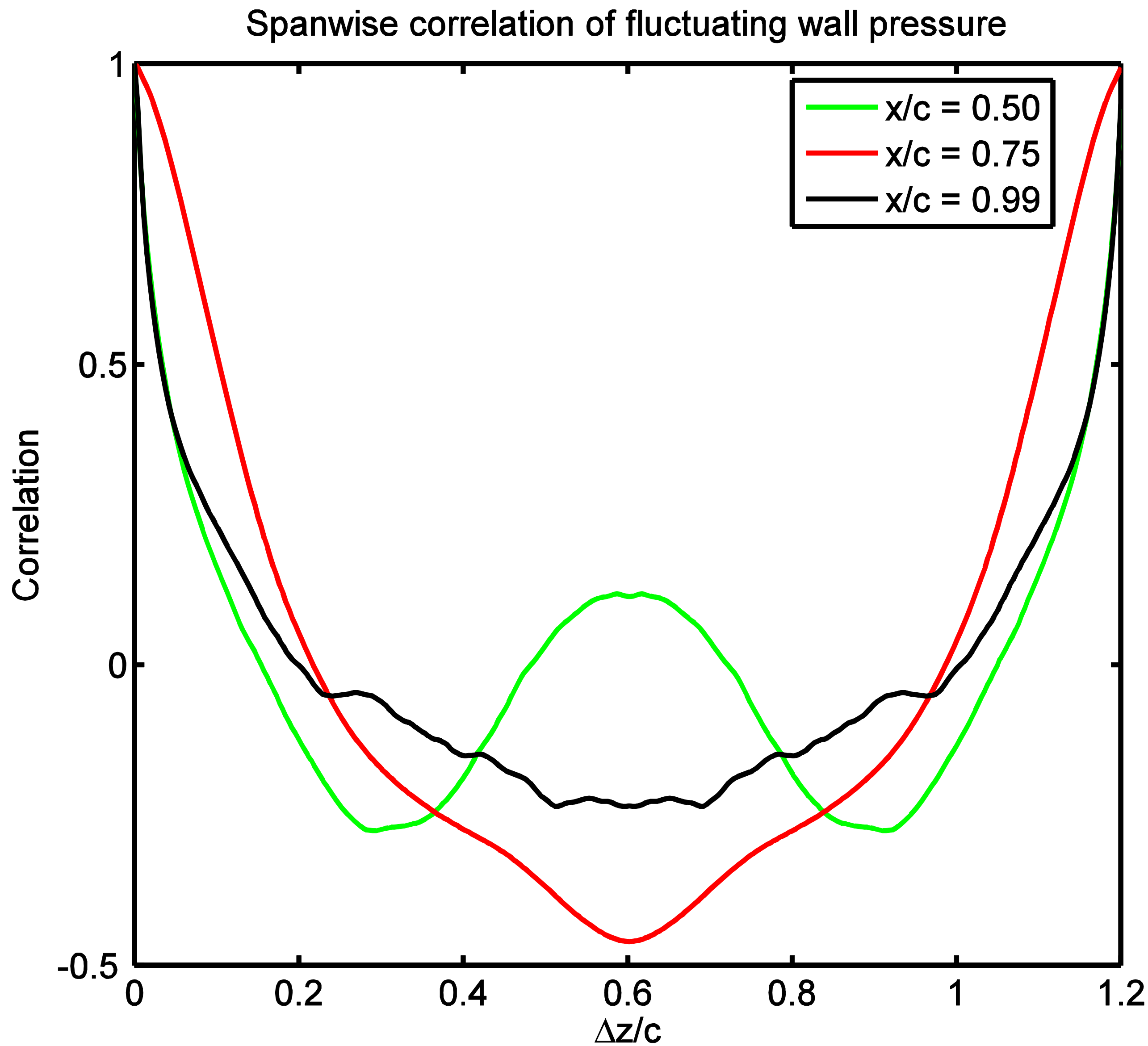
Stall Cells



Large-scale 3D flow instability



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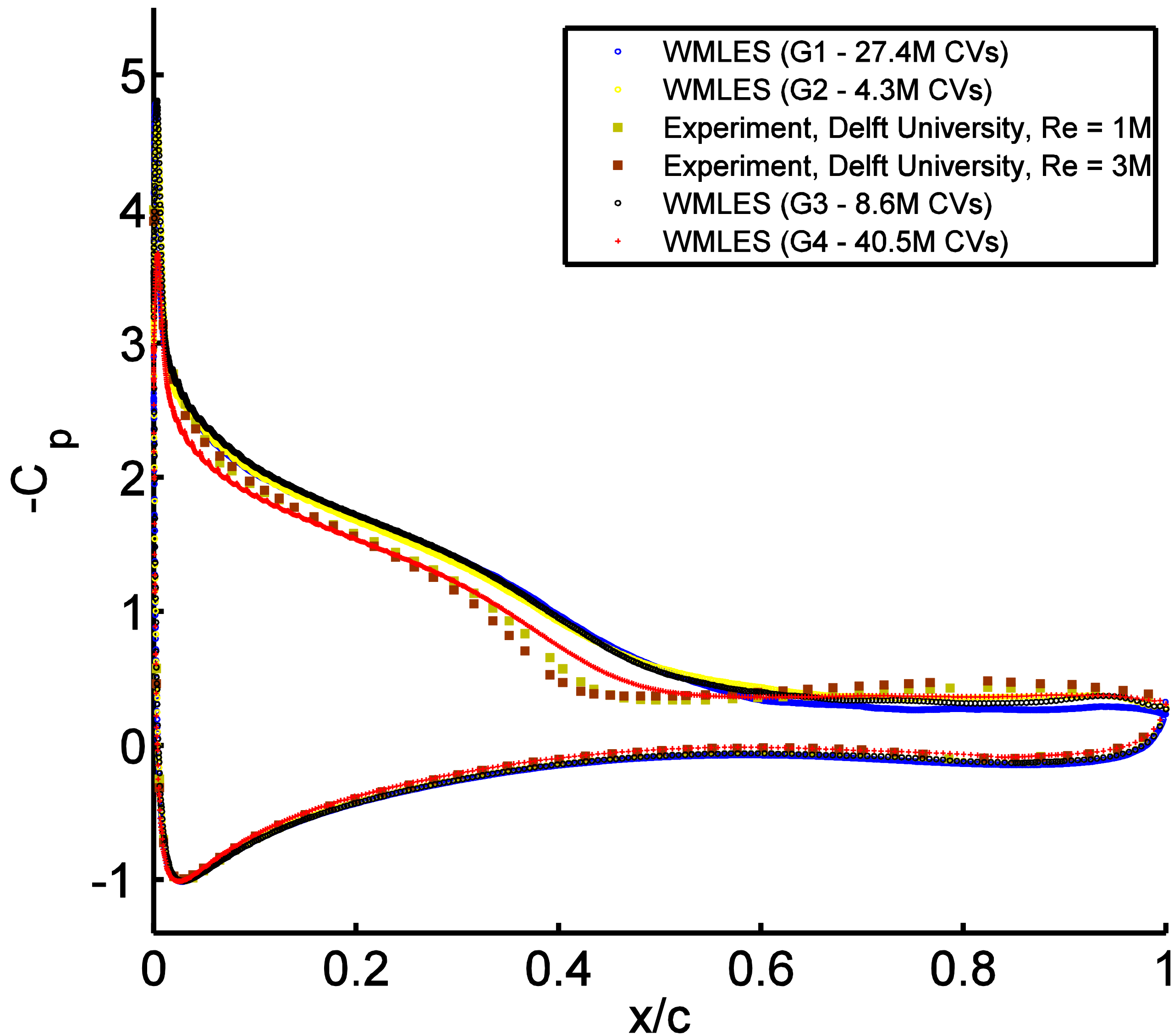
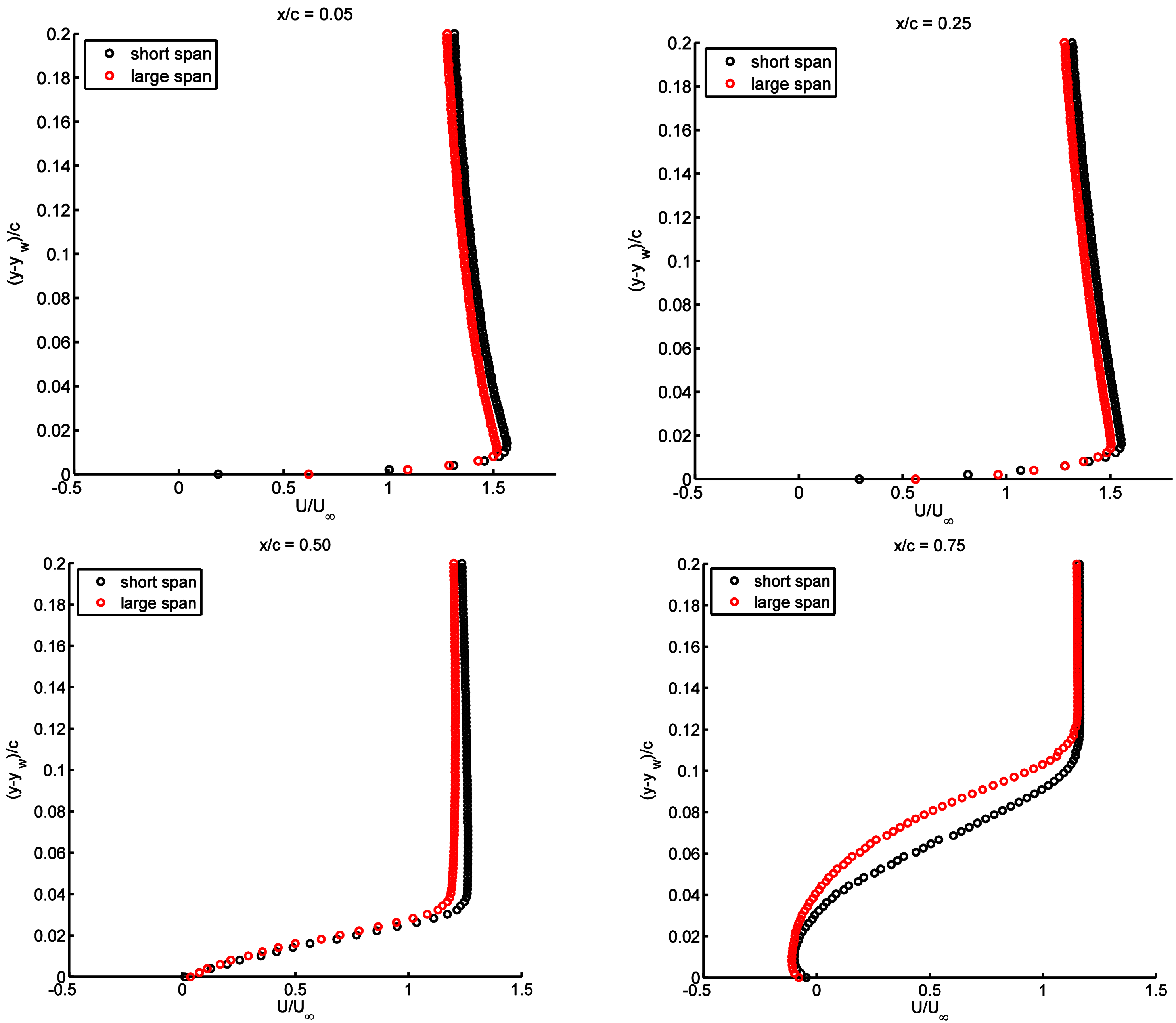


Boundary layer profiles on suction side



Comparison of C_L predictions

Dataset	Lift Coefficient
WMLES (short-span)	1.22+/-0.01*
WMLES (large-span)	**1.0754**
Delft (Re = 1M, AoA = 13.625)	1.109
Delft (Re = 2M, AoA = 13.13)	1.12
Delft (Re = 3M, AoA = 13.62)	1.105
RANS (Re = 1.5M, AoA = 13.2)	1.3915

- **WMLES (large-span) prediction within 3% of measurements**

*From calculations done on three different grids

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Conclusions

- *First* successful prediction of trailing edge noise from first principles at *full scale* Reynolds numbers
- Successful prediction of noise generated by an airfoil in the near stall regime
- Aerodynamic stall of a wind turbine airfoil at full-scale Reynolds numbers using WMLES – Novel large span calculation shows evidence for *stall cells*

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Acknowledgements

GE Global Research

CASCADE TECHNOLOGIES

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ASCR Leadership Computing Challenge

Flow Simulation

- Node-based finite volume scheme
- Implicit time advancement
- Second-order accurate in space and time
- Minimally dissipative – relies on discrete kinetic energy conservation for numerical stability
- Low-Mach, *weakly compressible* formulation
- High-frequency acoustic waves filtered out, low frequency acoustic waves retained
- Vreman model for subgrid scales of turbulence
- BCs – stress BC from wall model on the airfoil surface, Sponge BC at far-field boundaries to minimize spurious reflections
- Steady suction/blowing to force transition to turbulence

Far-field noise prediction

- Ffowcs Williams Hawkings Equation
- Amiet’s theory, Extended Amiet’s theory with leading edge back-scattering corrections from Roger and Moreau
- Chase-Chandiramani-Howe diffraction theory
- Finite-chord and finite-thickness effects investigated

WMLES of turbulent channel flow, $Re_\tau \sim 590$, DNS ~ 25M points, WMLES ~ 1M points